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KEPCO

OPERATIONAL POWER SUPPLIES

OPS
group VIII

1-7-97 DEP

Model OPS 150–7M

Serial No. E 88067

instruction manual

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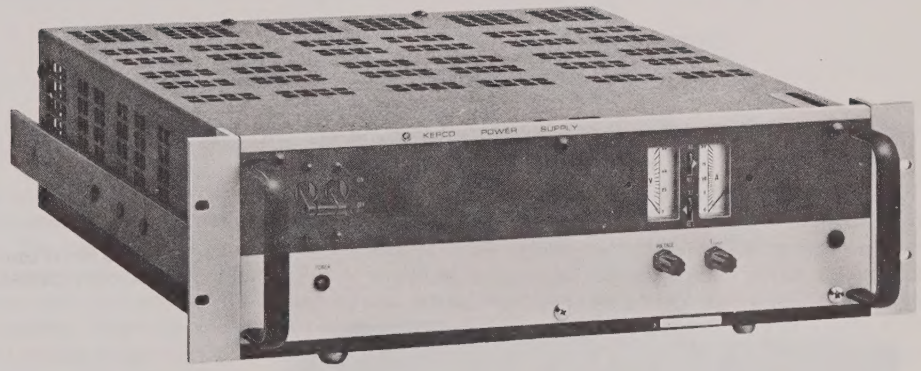
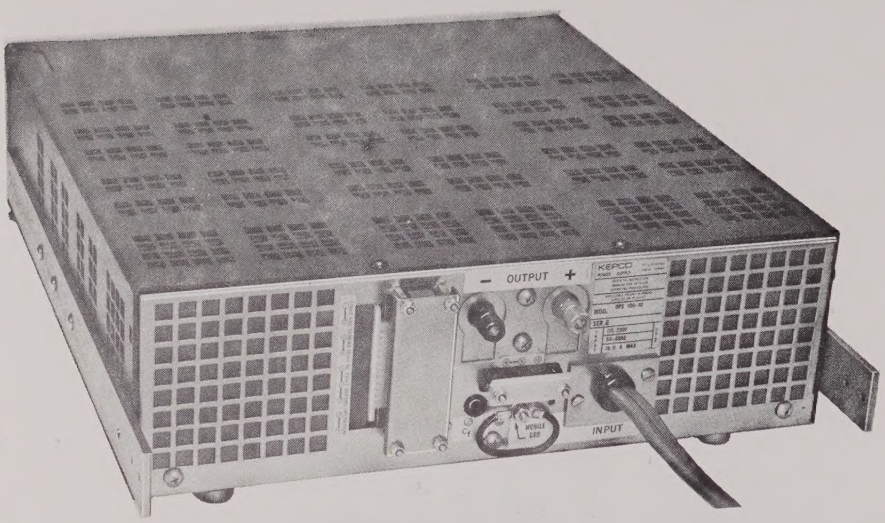


FIG. 1-1 OPS FULL-RACK POWER SUPPLY, TYPICAL FRONT VIEWS.

a) MODELS WITH 20A OR LESS
DC OUTPUT CURRENT



b) MODELS WITH 30A OR MORE
DC OUTPUT CURRENT

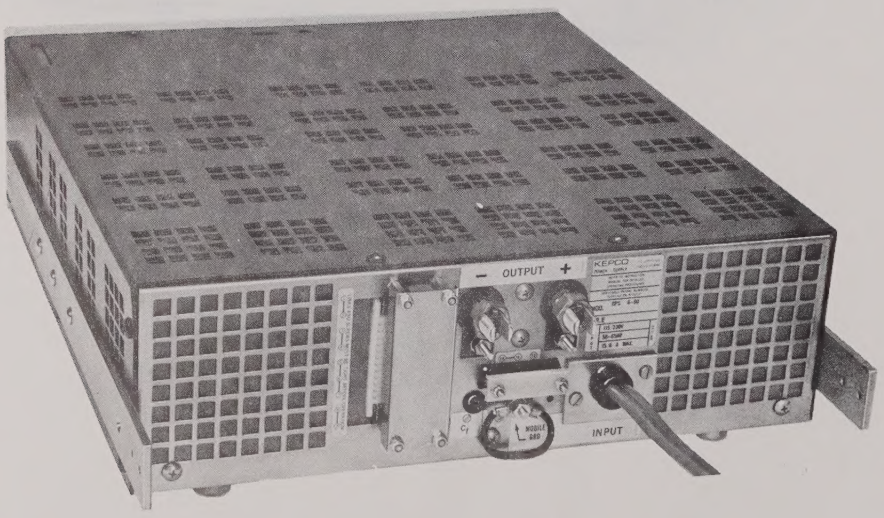


FIG. 1-2 OPS FULL-RACK POWER SUPPLY, TYPICAL REAR VIEWS.

SECTION I – INTRODUCTION

1-1 SCOPE OF MANUAL

1-2 This manual contains instructions for the installation, operation, and maintenance of the OPS GROUP VIII Operational Power Supplies, manufactured by Kepco, Inc., Flushing, New York.

1-3 GENERAL DESCRIPTION

1-4 The operational power supplies in the Kepco OPS VIII GROUP are designed for applications requiring a wide-band, programmable power source. OPS Power Supplies are unipolar devices which may be connected as d-c amplifiers, to deliver stabilized voltage, or current, or (by feedback) control other parameters.

1-5 OPS Power Supplies are built with an NPN "series regulator" or "pass-element" stage, functioning as a unipolar power amplifier. This power stage is driven via an "or" gate by either the voltage channel or the current limiter. The "voltage channel" with the voltage control amplifier is active in the "voltage mode" of operation, while the current limiter with its current control and current limit amplifiers is active in the "current limit mode." In the standard operating modes (local control) the output of the OPS is controlled by multiturn front panel controls. The prevailing operating mode is determined by the setting of the output controls (remote or front panel) and the value of the load resistance:

$$(\text{Load Resistance})\ R_L = \frac{E_O\ (\text{Output Voltage Setting})}{I_O\ (\text{Output Current Setting})}$$

For load resistances ***greater*** than R_L, the OPS will operate in the ***voltage mode.*** For load resistance ***smaller*** than R_L, the OPS will transfer into the ***current limit mode.***

1-6 The voltage channel of the OPS can be programmed by external resistance or voltage signals. Terminals for disconnecting the internal reference and controls and connecting external components, are provided at the rear. The low offset errors in the I–C front end of the voltage control channel allow very accurate tracking of all control signals. The voltage control amplifier is equipped with a built-in offset voltage control, which allows zero calibration of the output voltage. An internal reference voltage source (6.2V at 1 mA) is accessible for control, offset adjustments or biasing purposes. The low shunt capacity in the OPS output circuit permits rapid voltage programming or fast current recovery if the voltage channel is used with an external sensing and feedback circuit, for current stabilization.

1-7 The output current limit of the OPS is adjustable by the front panel control, or can be remotely controlled by a potentiometer or by d-c voltage signals over the full output current range. A current-control amplifier and additional rear terminals are provided for external control of the OPS current limit function. When operating in the current limit mode, the OPS functions as a current stabilizer, providing approximately 2% current stabilization in the local (front panel) control mode and 0.1% stabilization in the remote control mode. For precise current control, especially for relatively low output current requirements (mA range), the remote control mode is, therefore, especially suitable. If output currents in the μA range are required, a control method using the voltage channel and an external feedback control circuit is recommended. (Refer to Section III.)

1-8 The operational power supplies in the OPS GROUP VIII are constructed in a "full-rack" configuration. These instruments may be bench-operated, or mounted into standard equipment racks. The front and rear terminations of the OPS are:

a) A pair of dual range, ±3% output meters, indicating the d-c components of the output voltage and current.

b) "On-off" Power Switch/Circuit Breaker and a-c pilot light.

c) Multiturn controls for the local control of output voltage and current (disconnectable at the rear barrier-strip). OPS models have heavy duty rear output terminals, barrier-strip terminals for sensing and remote programming, as well as an a-c power cord.

1-9 The main chassis frame of the OPS is constructed from cold-rolled steel, as is the perforated wrap-around cover. The front panel is constructed from aluminum. (Refer to FIG. 1-3 for material gauge and finish.)

1-10 SPECIFICATIONS, GENERAL

a) A-C SOURCE POWER INPUT: 105 to 125V a-c or 210 to 250V a-c, selectable (refer to Section II, FIG. 2-2). A-C input current: see Table 1-1.

b) OPERATING TEMPERATURE RANGE: (−)20°C to (+)71°C without derating of the output.

c) STORAGE TEMPERATURE RANGE: (−)40°C to (+)85°C.

d) ISOLATION FROM GROUND: Output isolated from chassis (ground). A maximum of 500 volts (d-c or p-p) may be placed in series with either output lead. COMMON MODE CURRENT from output to ground: <5 microamperes (rms), <50 microamperes (p-p) at 60 Hz.

e) COOLING: Two high efficiency, single-bearing fans, permanently lubricated, with special nonmetal blades.

1-11 SPECIFICATIONS, PERFORMANCE

a) OUTPUT RATINGS, OUTPUT IMPEDANCE, AND A-C INPUT SOURCE CURRENT: (Refer to Table 1-1.)

MODEL	D-C OUTPUT RANGE		OUTPUT IMPEDANCE		SOURCE CURRENT at 125V a-c (Amps, rms)
	VOLTS	AMPS	VOLTAGE MODE D-C OHMS + SERIES L	CURRENT MODE[1] D-C OHMS + SHUNT C	
OPS 6–90M	0–6	0–90	3.5 μΩ + 100 μH	5.5 kΩ + 1800 μF	15.7
OPS 15–50M	0–15	0–50	15 μΩ + 100 μH	10 kΩ + 1000 μF	16.6
OPS 25–40M	0–25	0–40	31 μΩ + 100 μH	12.5 kΩ + 800 μF	21.0
OPS 36–30M	0–36	0–30	60 μΩ + 75 μH	16.6 kΩ + 600 μF	19.0
OPS 55–20M	0–55	0–20	138 μΩ + 75 μH	25 kΩ + 400 μF	18.0
OPS 75–15M	0–75	0–15	250 μΩ + 50 μH	33 kΩ + 150 μF	18.0
OPS 100–10M	0–100	0–10	620 μΩ + 50 μH	50 kΩ + 100 μF	17.0
OPS 150–7M	0–150	0–7	1.1 mΩ + 50 μH	73 kΩ + 70 μF	18.0

[1]Current mode using an external current sensing and feedback circuit. Impedance data based on a 1-volt sample.

TABLE 1-1 SPECIFICATIONS, OPS GROUP VIII.

b) VOLTAGE CONTROL CHANNEL

1) D-C OPEN-LOOP GAIN: $>0.5 \times 10^6$ volts per volt.

2) OFFSETS: See Table 1-2. Note: This tabulation specifies the maximum change in the amplifier offsets for the listed variation of the "Influence Quantities." OPS output performance for ***your*** application can be calculated by inserting these specifications into the "error equation" presented in Section IV of this manual.

INFLUENCE QUANTITY	VOLTAGE CONTROL CHANNEL		REFERENCE
	OFFSET VOLTAGE ΔE_{io}	OFFSET CURRENT ΔI_{io}	6.2V ±5%
SOURCE: 105–125V a-c	<10 μV	<2 nA	<0.0001%
LOAD: No load – full load	<200 μV(1)	<5 nA	–
TIME: 8-hour [drift]	<20 μV	<2 nA	<0.005%
TEMPERATURE: Per °C	<20 μV	<5 nA	<0.005%
RIPPLE AND NOISE:(3) rms	0.02% of E_o max or 6 mV(2)		–
RIPPLE AND NOISE:(3) p-p(4)	0.25% of E_o max or 50 mV(2)		–

(1) ΔE_{io} for load in current stabilization mode is ΔE_o/open-loop gain. ΔE_o is the compliance voltage change.
(2) Whichever is greater.
(3) One terminal must be grounded or connected so that common-mode current does not flow through the load or through a current-sensing resistor.
(4) 20 Hz to 10 MHz.

TABLE 1-2 OFFSET AND REFERENCE SPECIFICATIONS.

3) PROGRAMMING: As a precision d-c source the output voltage of the OPS can be controlled using the internal reference source (1 mA ±10%, calibrated by built-in I_b ADJ. control) and the front panel rheostat (VOLTAGE CONTROL) or an external resistance, at a programming ratio of 1000 ohms per volt. As a unipolar amplifier, the (inverting) input of the voltage mode amplifier is available for programming with external voltage or current input signals.

4) DYNAMICS

MAXIMUM SLEWING RATE: (Maximum rate of change achievable by overdriving or forcing): >100 volts per milliseconds for OPS models rated for ***less*** than 20 amperes output current; >50 volts per milliseconds for OPS models rated for 20 amperes and above.

FULL POWER FREQUENCY RESPONSE (SINE WAVE):

$$f_{max} = \frac{\text{Slewing Rate}}{\pi E_{p\text{-}p}} \text{ (Volts/Second)},$$

where $E_{p\text{-}p}$ represents the maximum rated output voltage of the OPS model.

PROGRAMMING TIME CONSTANT: The PROGRAMMING TIME CONSTANT expresses the programming speed of the OPS in the linear operating region. The OPS output voltage will respond to an input step voltage with an exponential waveform. The rise time of this exponential output waveform, from zero to 63% of the final output voltage is defined by Kepco as the PROGRAMMING TIME CONSTANT. The PROGRAMMING TIME CONSTANT depends (to a first approximation) on the feedback resistance (R_f) and the feedback capacitance (C_f) used in the programming circuit:

$$\text{PROGRAMMING TIME CONSTANT } (\tau) \approx R_f C_f.$$

-3 dB FREQUENCY RESPONSE: The sine wave frequency response of the OPS in the linear operating region is given by

$$f_{(-3\,dB)} = \frac{1}{2\pi\tau}, \text{ where } \tau \text{ is the PROGRAMMING TIME CONSTANT.}$$

5) OUTPUT LOADING: Maximum capacitive load: 0.001 μF. ***For inductive loads, the OPS must be protected with a series diode in one of the output leads from the possible back EMF generated by the load.***

6) CURRENT RECOVERY: The OPS voltage channel may be used to stabilize output current, using an external feedback and sensing circuit. The speed with which the stabilized output current returns to the stabilization band following a step in load voltage (CURRENT RECOVERY) is either governed by the time constant of the load/feedback resistance and feedback capacitance, or by the ratio I_O/C_S (I_O = current setting, C_S = tabulated shunt capacitance), whichever is smaller. See Table 1-1 for tabulated shunt capacitances.

7) OFFSET NULLING: The intial (fixed) part of the voltage amplifier offset voltage (E_{io}) can be zeroed by a built-in control.

c) CURRENT LIMIT CIRCUIT

1) LOCAL (FRONT PANEL) CONTROL. The current limit circuit offers approximately 2% current stabilization in the "Current Mode" of operation. The output current limit can be controlled from approximately 2% to the rated maximum.

2) REMOTE CONTROL. A built-in current control amplifier permits the remote control of the output current limit from approximately 0.1% to the maximum rated value. In the remote control mode approximately 0.1% stabilization is available when operating in the "Current Mode." Remote control can be exercised by a potentiometer or by a d-c voltage signal.

1-12 SPECIFICATIONS, MECHANICAL

a) DIMENSIONS, MATERIAL AND FINISH: See "Mechanical Outline Drawing," this section, FIG. 1-3.

b) WEIGHT: OPS GROUP VIII: Approximately 100 pounds (45 kg.).

c) TERMINATIONS: See Section II, FIGS. 2-3 and 2-4.

d) METERS: Two dual-range (100% and 10% of the d-c component of the output voltage and output current), 2-inch recessed panel meters, accuracy ±3% of full scale are provided.

e) MOUNTING: Four feet are provided for bench operation. Rack mounting possible by means of side flanges and additional side and/or rear support. (See installation drawing, Section II, FIG. 2-5.)

1-13 ACCESSORIES

a) KEPCO MODELS FSB–1 (1 3/4 inches high), FSB–3 (3 1/2 inches high), and FSB–5 (5 1/4 inches high).

FILLER SUPPORT BRACKETS. The OPS cannot be mounted into an equipment rack with its side flanges as the sole support. The FSB filler brackets provide the necessary additional support, if no other means of support (rack-shelf, slide, etc.) is available. The height of the bracket is selected according to the available rack space.

SECTION II – INSTALLATION

2-1 UNPACKING AND INSPECTION

2-2 This OPS GROUP VIII OPERATIONAL POWER SUPPLY (OPS) has been thoroughly inspected and tested prior to packing and is ready for operation. After careful unpacking, inspect for shipping damage before attempting to operate. Perform the preliminary operational check as outlined in par. 2-8 below. If any indication of damage is found, file an immediate claim with the responsible transport service.

2-3 TERMINATIONS

a) FRONT PANEL: Refer to FIG. 2-3 and Table 2-2.

b) REAR: Refer to FIG. 2-4 and Table 2-3.

c) INTERNAL ADJUSTMENTS AND CALIBRATIONS: Refer to FIG. 2-1 and Table 2-1.

REFERENCE DESIGNATION	CONTROL	PURPOSE	ADJUSTMENT PROCEDURE
C210	C_f Adjustment	Dynamic Stability Adjustment	Section III, par. 3-17
R4	I_b Adjustment	Control Current Calibration	Section III, par. 3-15
R14	E_{io} Null Adjustment	Output Voltage Zero Calibration	Section III, par 3-15
R16,36,43	Lag Adjustments	Dynamic Stability Adjustments	Section III, par. 3-17
R19	I_o max Adjustment	Maximum Output Current Calibration	Section V, par. 5-4
R41	I_o ZERO	Output Current Zero Calibration	Section III, par. 3-63

TABLE 2-1 INTERNAL CONTROLS.

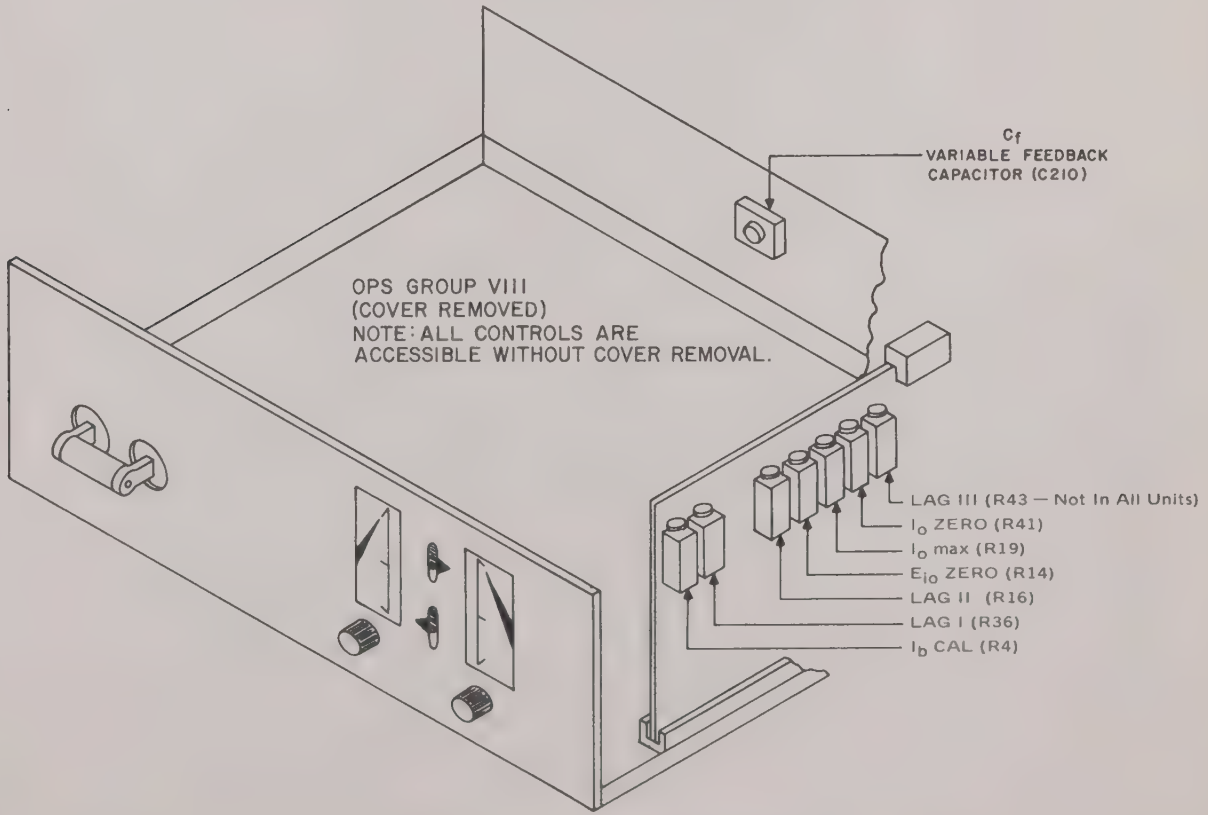


FIG. 2-1 LOCATION OF INTERNAL CONTROLS.

2-4 A-C INPUT REQUIREMENTS

2-5 This power supply is normally delivered for operation on a single phase, nominal 115V a-c line. For conversion to 230V a-c line operation, refer to FIG. 2-2. Remove the two links between transformer terminals (1)–(2) and (3)–(4). Reconnect one (1) link between terminals (2) and (3). DO NOT CHANGE ANY OTHER WIRING ON THE TRANSFORMERS.

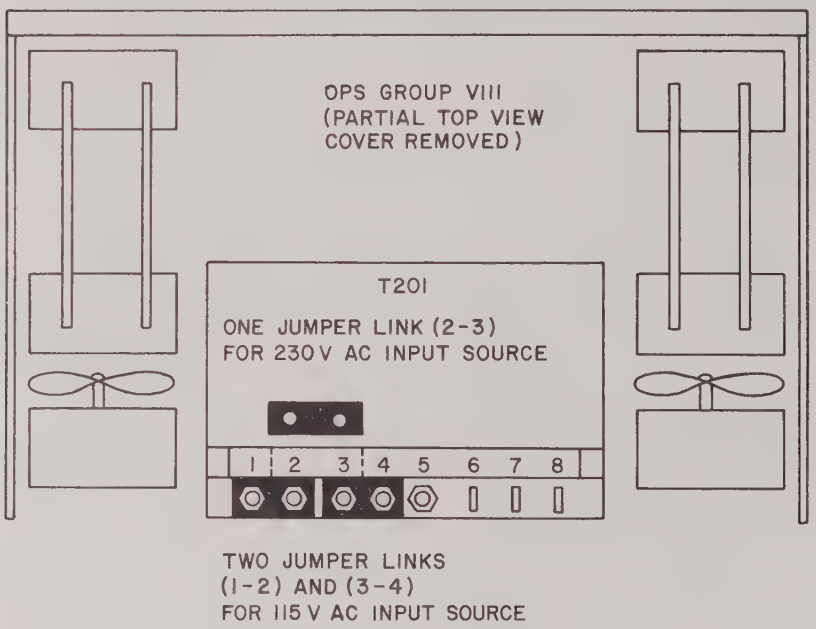


FIG. 2-2 CONVERSION TO 230V A-C NOMINAL LINE OPERATION.

2-6 COOLING

2-7 The power transistors and rectifiers in the OPS are maintained within their operating temperature range by means of two high efficiency heat sink assemblies, cooled by internal fans. SIDE PANEL OPENINGS AND THE TOP OF THE CASE MUST BE KEPT CLEAR FROM OBSTRUCTIONS TO INSURE PROPER AIR CIRCULATION. Periodic cleaning of the interior of the OPS is recommended. If the OPS is rack mounted, or installed into confined spaces, care must be taken that the temperature immediately surrounding the OPS does not rise above the specified limit (71°C).

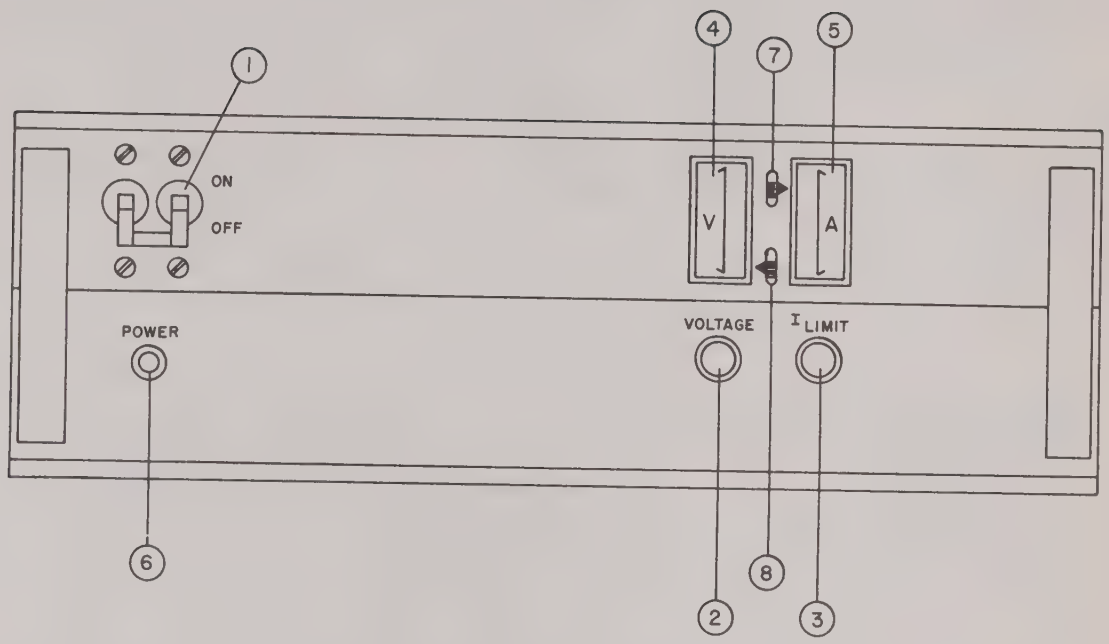


FIG. 2-3 FRONT PANEL CONTROLS AND TERMINATIONS.

NO.	CONTROL OR TERMINATION	FUNCTION
1.	A-C POWER SWITCH/ CIRCUIT BREAKER	TURNS A-C POWER LINE, "ON" OR "OFF" AND PROTECTS POWER SUPPLY INPUT CIRCUITRY
2.	VOLTAGE CONTROL	ADJUSTS OUTPUT VOLTAGE FROM 0–E_o max
3.	CURRENT LIMIT CONTROL	ADJUSTS CURRENT LIMIT FROM 0–105% I_o max
4.	VOLTMETER	MONITORS OUTPUT VOLTAGE, 0–E_o max
5.	AMMETER	MONITORS OUTPUT CURRENT 0–I_o max
6.	A-C PILOT LIGHT	ENERGIZES WHEN A-C POWER IS "ON"
7.	METER RANGE SWITCH AMPERE	MAY BE SET TO FULL SCALE READING OF MAXIMUM OR 1/10 OUTPUT
8.	METER RANGE SWITCH VOLTS	MAY BE SET TO FULL SCALE READING OF MAXIMUM OR 1/10 OUTPUT

TABLE 2-2 CONTROLS AND TERMINATIONS, FULL-RACK OPS GROUP VIII MODELS, FRONT.

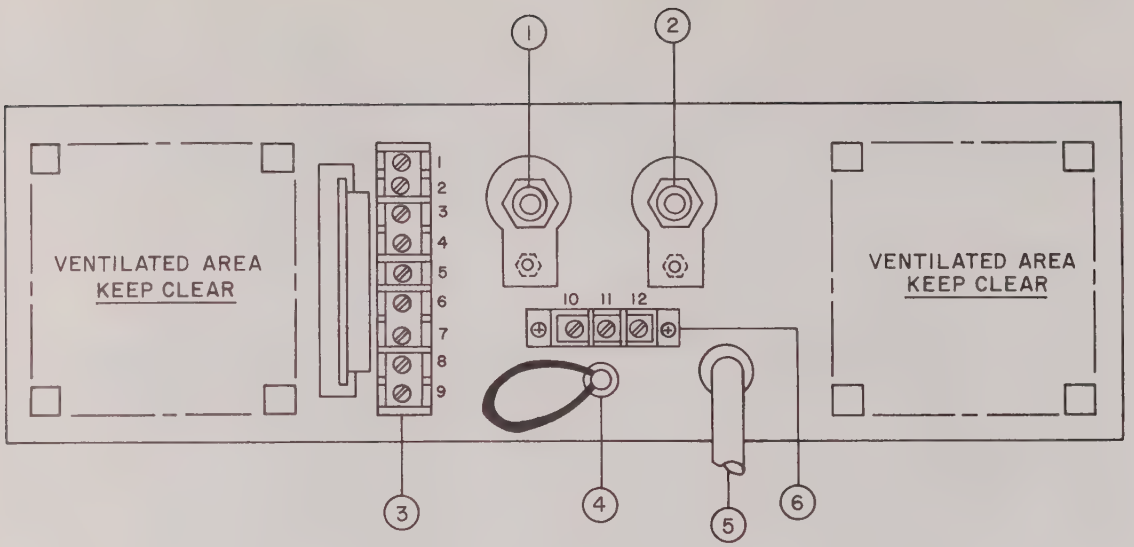


FIG. 2-4 REAR TERMINATIONS, OPS GROUP VIII.

NO.	TERMINATION	FUNCTION
1.	(−) OUTPUT	[1]NEGATIVE LOAD TERMINAL WITH GROUNDING POST
2.	(+) OUTPUT	[1]POSITIVE LOAD TERMINAL WITH GROUNDING POST
3.	REAR BARRIER-STRIP	PROGRAMMING AND MONITOR TERMINALS: (1) (+) OUTPUT MONITOR (2) (+) ERROR SENSING (3) (−) OUTPUT MONITOR (4) (−) ERROR SENSING (5) INTERNAL VOLTAGE CONTROL (6) NULL JUNCTION (AMPLIFIER INPUT) (7) REFERENCE RESISTOR (8) REFERENCE VOLTAGE (9) REFERENCE RESISTOR
4.	CHASSIS GROUND CONNECTION	[1]FLOATING GROUND LEAD TO GROUND EITHER THE (+) OR (−) OUTPUT VIA GROUND POST
5.	A-C INPUT	3-WIRE SAFETY LINE CORD
6.	REAR BARRIER-STRIP	CURRENT LIMIT PROGRAMMING TERMINALS: (10) OUTPUT CURRENT REFERENCE (11) OUTPUT CURRENT CONTROL (12) OUTPUT CURRENT COMMON

[1]Models with less than 25A d-c output current do not have grounding posts. The chassis connection on these models is a terminal instead of a floating ground lead.

TABLE 2-3 REAR TERMINATIONS, FULL-RACK OPS GROUP VIII.

2-8 PRELIMINARY CHECKOUT. NOTE: Jumper links on both rear barrier-strips must be connected as shown in FIG. 2-4.

2-9 A simple operating check after unpacking and before permanent installation is advisable, to ascertain whether the OPS has suffered damage resulting from shipment. Please refer to FIGS. 2-3, 2-4 for the location of the operating controls and output terminals.

a) Connect OPS to 115V a-c input source or refer to par. 2-4 for 230V a-c operation, if required.

b) Turn CURRENT LIMIT CONTROL fully clockwise. Turn VOLTAGE CONTROL fully counter clockwise. Both VOLTMETER RANGE and AMMETER RANGE switch should be in the "x1" position.

c) Turn A-C POWER SWITCH "on." The A-C PILOT LIGHT should be energized. Slowly turn VOLTAGE CONTROL clockwise and observe the gradual increase of the output voltage. Turn counterclockwise again, until about one-tenth of the maximum output voltage is reached. Set VOLTMETER RANGE switch(1) to the "x0.1" positions.(1) The VOLTMETER should now read full scale again. Turn A-C POWER SWITCH "off."

d) Place a short circuit across the output.(1) Turn CURRENT LIMIT CONTROL counterclockwise. Turn A-C POWER SWITCH "on." Slowly turn CURRENT LIMIT CONTROL clockwise and observe the gradual increase in output current. Turn counterclockwise until about one-tenth of the maximum output current is reached. Set AMMETER RANGE switch to the "x0.1" position. The AMMETER should now read full scale again.

e) Return VOLTMETER RANGE and AMMETER RANGE switches to their "x1" positions.

(1) **CAUTION**

1) DO NOT SWITCH TO THE "x0.1" RANGES BEFORE THE OUTPUT OF THE POWER SUPPLY (VOLTAGE OR CURRENT) IS BELOW 10% OF THE MAXIMUM RATED VALUES.

2) CONNECT SHORT CIRCUIT (OR LOAD) TO THE HEAVY DUTY OUTPUT TERMINALS, NOT TO THE BARRIER-STRIP. BARRIER-STRIP TERMINALS ARE FOR VOLTAGE MONITORING AND PROGRAMMING CONNECTIONS ONLY.

2-10 GROUNDING

a) A-C GROUND. The OPS is equipped with a 3-wire safety line cord and polarized plug. The third (green) wire in the line cord is connected to the chassis and the case of the unit. If a 2-terminal receptacle in combination with an adapter is used, it is imperative that the chassis of the OPS be returned to a-c ground with a separate lead.

b) D-C GROUND. The d-c output is isolated from the a-c power line and from any direct connection to chassis or ground. The maximum voltage that can be supported between either output terminal and ground or chassis is 500 volts d-c plus the maximum output voltage of the power supply. Either side of the output may be grounded. Convenient grounding terminals are provided at the front panel binding post (if OPS is so equipped) and at the rear of OPS.

NOTE:

Specified ripple and noise figures for operational power supplies are valid *only* with one side of the output/load circuit returned to a common ground point (refer to Section I, Table 1-2). The *positive* side of the OPS output is shown grounded in all application diagrams, since it is "common" to both, internal reference source and any external signal input source. If the application requires, the *negative* side of the OPS output may be signal-grounded or the OPS output may be left ungrounded (floating). In the latter case, however, the ripple and noise level will increase somewhat, since the common-mode current (specified in Section I, par. 1-10d) flows now through the load (Voltage Mode) or through the external sensing resistor (Current Mode). The signal ground point in the OPS/load circuit must consist of a *single point* only, to which all input source grounds, shields and load grounds are connected. Multiple signal grounds in the OPS output/load circuit cause "ground-loop" problems, since noise signals develop across the impedances between the multiple ground points. The exact physical location of the "best" single ground point must be carefully selected for minimum ripple/noise output.

2-11 INSTALLATION (Refer to Section I, FIG. 1-3 "Mechanical Outline Drawing," and to FIG. 2-5, this section)

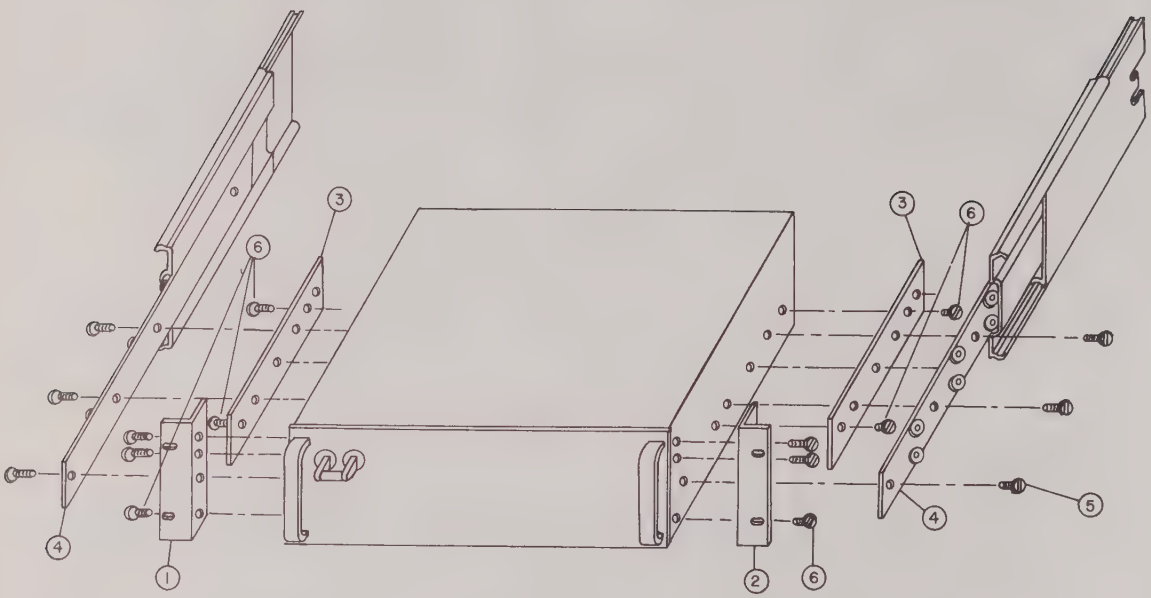
2-12 With its four (4) removable aluminum bottom feet, the OPS may be operated on the bench, or placed on an equipment shelf for convenient operation. For bench operation, the FRONT ANGLE BRACKETS and the FILLER BRACKETS may be removed.

2-13 The OPS may be installed into a standard equipment rack (19 inches wide). The provided FRONT ANGLE BRACKETS (Side Flanges) are drilled for standard rack dimensions. Since the FRONT ANGLE BRACKETS are not sufficient to support the full weight of the OPS, additional means of support must be provided, using one of the three methods described below:

a) CHASSIS SLIDES. The OPS is equipped on its sides with FILLER BRACKETS, which are predrilled for a number of "JONANTHAN" slide types. (See Section I, FIG. 1-3.)

b) FILLER SUPPORT BRACKETS. The Kepco FSB Filler Support Brackets (see Section I, par. 1-14 "Accessories") are ideally suited to provide additional support at the rear edge (or at the sides) in rack cabinets where suitable mounting channels or angles are avaliable.

c) MOUNTING PLATFORM. A rigid mounting platform, if available in the equipment rack, can provide the necessary support for the OPS. The platform must be adjusted in such a way, that the mounting holes in the FRONT ANGLE BRACKETS line-up with the threaded holes in the side channels of the equipment rack.



CAUTION

WHEN INSTALLING THIS GROUP OF MODELS IN A RACK OR CABINET, THE MODEL MUST BE SUPPORTED, EITHER BY USING CHASSIS SLIDES AS SHOWN, BY FIXED ANGLE-BRACKETS (KEPCO FSB FILLER SUPPORT BRACKETS, SEE PAR. 1-3a "ACCESSORIES") OR BY A RIGID PLATFORM MOUNTED IN THE RACK OR CABINET. (THESE INSTALLATION AIDS ARE NOT SUPPLIED.)

RACK MOUNTING ACCESSORIES PART LIST:

ITEM	DESCRIPTION	QTY.
1	FRONT ANGLE LEFT	1
2	FRONT ANGLE RIGHT	1
3	FILLER BRACKET	2
4	SLIDES: 110 QD-24-1 JONATHAN SERIES	2
5	10—32 SCR. BDG. HD.	10
6	10—32 FLATHEAD 82°	6

NOTE: ITEM (4) NOT SUPPLIED
SEE OUTLINE DWG. (FIG. 1-3) FOR INSTALLATION OF OTHER SLIDES IN THE "110 QD" SERIES.

FIG. 2-5 RACK-INSTALLATION, "FULL-RACK" MODELS.
NOTE: INSTALL ITEMS IN THE ORDER OF THEIR CALL-OUT NUMBERS.

3-1 INTRODUCTION

3-2 The operational power supplies in Kepco's OPS GROUPS VI, VII, and VIII are wide-band, high-gain power sources, which can be used in a great variety of applications. Some examples are:

a) The OPS may be operated as a precision stabilized voltage source with local (front panel) or external (remote) control of the output voltage. The current channel serves as a continuous adjustable output current limiter in this application. (See, for example, FIG. 3-1.) Output control can be exercised by means of remote resistance, or by external voltage or current signals or by conductance.

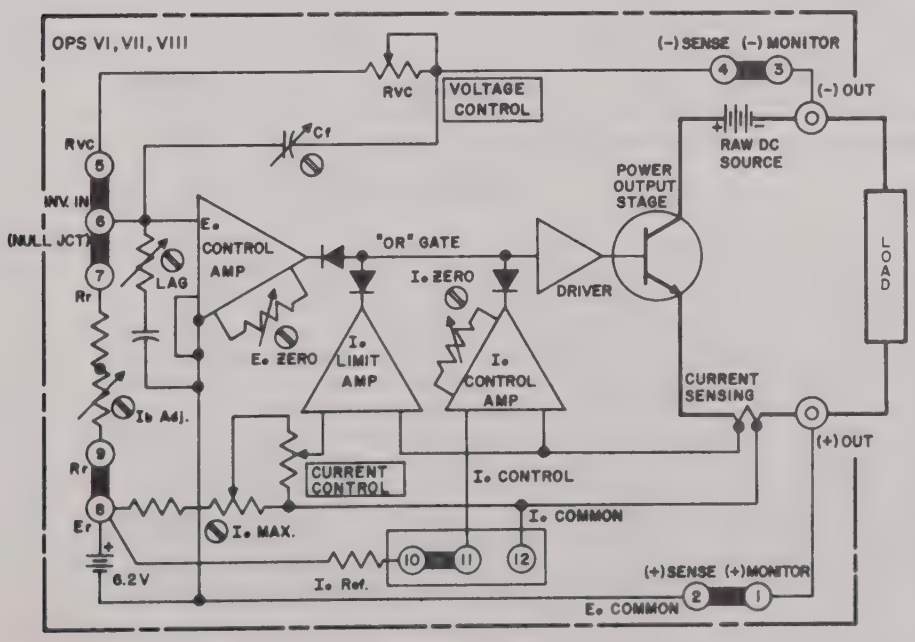
b) The OPS may be operated as a precision stabilized current source with external current sensing and control, using the voltage channel. In this application, voltage limiting must be provided externally. (See, for example, FIG. 3-13.) This mode of operation is especially suited for very small output current (μA range).

c) The OPS may be operated as a unipolar, wide-band amplifier, using resistive feedback as a gain control and an external signal source with input resistor. The current channel serves as a continuously adjustable output current limiter in this application. (See, for example, FIG. 3-7.)

d) The output current limit of the OPS is adjustable by the front panel control, or can be remotely controlled by a potentiometer or by d-c voltage signals over the full output current range. A current-control amplifier and additional rear terminals are provided for external control of the OPS current limit function. When operating in the current limit mode, the OPS functions as a current stabilizer, providing approximately 2% current stabilization in the local (front panel) control mode and 0.1% stabilization in the remote control mode. For precise current control, especially for relatively low output current requirements (mA range), the remote control mode is, therefore, especially suitable. If output current in the μA range are required, a control method using the voltage channel and an external feedback control circuit is recommended. (Refer to Section III.)

3-3 Detailed examples for the briefly described applications above will be given in the following paragraphs of this section. Before actual operation, however, the following important general comments, applicable to ***all*** programming circuits, should be considered:

a) DIAGRAMS (see FIG. 3-1). Application and test setup diagrams on the following pages show the symbolic and simplified representation of the OPS GROUPS VI, VII, and VIII power supply circuit. The encircled terminal numbers shown on these diagrams correspond to the actual barrier-strip terminal numbers on the rear of the OPS. (Refer to Section II, FIG. 2-4.)



NOTE 1)
Jumper link positions as shown are for standard power supply operation, local (front panel) control.

NOTE 2)
The Model OPS 6—90M uses an additional amplifier which is not shown in the simplified diagram. This amplifier (A_M in the Main Schematic), is used to amplify the sensing resistor voltage drop by a factor of 20.

NOTE 3)
NOMENCLATURE AND ABBREVIATIONS USED IN *ALL* SIMPLIFIED DIAGRAMS:

C_f	=	Adjustable, Feedback Capacitor
E_o	=	Output Voltage
E_r	=	Reference Voltage
I_b	=	D-C Control Current
INV. INPUT	=	(Inverting) Input to the (NULL) Voltage Mode Control Amplifier
I_o	=	Output Current
LAG	=	Adjustable Lag Network
R_{cc}	=	Current Control Resistor
R_r	=	Reference Resistor
R_s	=	Current Sensing Resistor
R_{vc}	=	Voltage Control Resistor

FIG. 3-1 SYMBOLIC CIRCUIT DIAGRAM, OPS GROUPS VI, VII, VIII.

b) LOAD CONNECTIONS. The most basic interconnection between the OPS and a primarily resistive and relatively constant load, located close to the OPS, consists in the 2-wire connection as shown in FIG. 3-1. ***The load wire size should be as large as practicable*** to keep the series resistance and inductance of the load wire small. ***In addition, the load wire pair should be tightly twisted*** to reduce possible noise pickup from magnetic fields. This 2-wire connection, as illustrated in FIG. 3-1 is recommended ***only*** for applications, where the voltage drop in the load wires is not important, as for example, if the OPS is used in a ***constant current mode.*** For operation in a ***voltage or amplifier mode,*** where a minimum load effect is required at a remote load, a 4-wire sensing connection illustrated in FIG. 3-2 should be used. A twisted, shielded pair of wires from the OPS "sensing" terminals directly to the load, will compensate for load wire voltage drops up to 0.5 volts per load wire. ***Observe polarities:*** The ***negative sensing wire*** (from terminal 4) must go to the ***negative load wire*** at the load; the ***positive sensing wire*** (from terminal 2), goes to the ***positive load wire*** at the load. The jumper links between terminals (3)—(4) and (1)—(2) must be removed for the 4-wire error sensing technique.

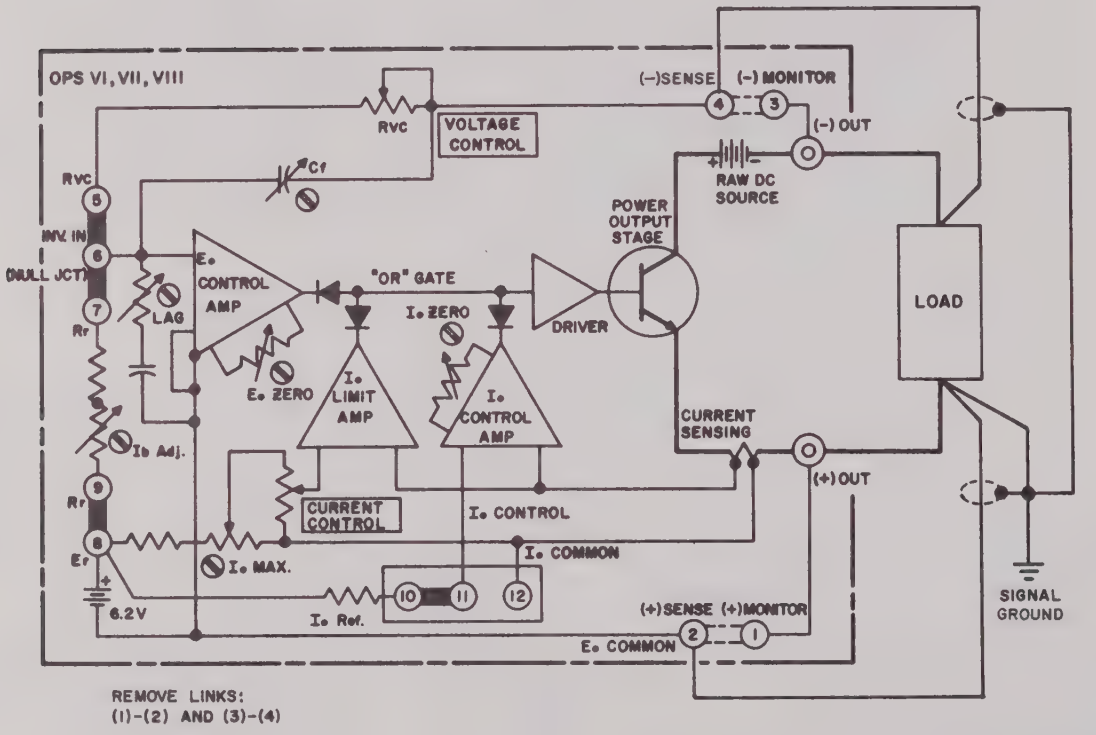


FIG. 3-2 REMOTE ERROR SENSING.

c) D-C (SIGNAL) GROUNDING. Specified ripple and noise figures for operational power supplies are valid ***only*** with one side of the output/load circuit returned to a common ground point (refer to Section I, Table 1-2). The ***positive*** side of the OPS output is shown grounded in all application diagrams, since it is "common" to both, internal reference source and any external signal input source. If the application requires, the ***negative*** side of the OPS output may be signal-grounded or the OPS output may be left ungrounded (floating). In the latter case, however, the ripple and noise level will increase somewhat, since the common-mode current (specified in Section I, par. 1-7g) flows now through the load (Voltage Mode) or through the external sensing resistor (Current Mode). The signal ground point in the OPS/load circuit must consist of a ***single point*** only, to which all input source grounds, shields and load grounds are connected. Multiple signal grounds in the OPS output/load circuit cause "ground-loop" problems, since noise signals develop across the impedances between the multiple ground points. The exact physical location of the "best" single ground point must be carefully selected for minimum ripple/noise output.

d) EXTERNAL PROGRAMMING RESISTORS. External programming resistors, decades or rheostats should be ***high-quality units with low temperature coefficients.*** The wattage rating of the feedback resistance should be at least 10-times that of their calculated power dissipation to avoid drift and dissipation problems.

e) ACTIVE PROGRAMMING SOURCES. Voltage or current sources used for input or reference signals on the OPS should have temperature and time (drift) specifications equal or better than that of the OPS. CAUTION: A-C powered sources must have their "common" input lead consistent with that of the OPS to be programmed. Older signal generators, for example, with their common lead connected to their case, can only be used if the required input signal polarity allows their case to be connected to the "common" of the OPS.

f) EXTERNAL SWITCHES. Step-switch devices, used in the feedback path of the voltage channel of the OPS (for step-voltage programming for example) must be of the "make before break" type to avoid opening the feedback loop during switching. A momentary open feedback loop causes large voltage "spikes," since the output voltage of the OPS will rise to its maximum value while trying to respond to an open (infinite) feedback resistance.

g) EXTERNAL LEADS. Shielded leads should be used for all input connections to the OPS control channels. The shield should be connected (single-ended) to the chosen signal ground point.

3-4 OPS AS A LOCALLY CONTROLLED VOLTAGE OR CURRENT SOURCE

3-5 The OPS is delivered with its rear terminations connected for operation as a voltage or current source, controlled by the built-in front panel rheostats for output voltage and output current. The range of the front panel controls is factory adjusted to cover the rated output range of each OPS model. These controls can be recalibrated if required by following the procedure given in Section V of this manual.

3-6 Whether the OPS operates in the voltage stabilizing or current limit mode, is determined by the setting of both front panel controls and by the value of the load resistance:

$$R_L \text{ (Load Resistance)} = \frac{E_o \text{ (Output Voltage Setting)}}{I_o \text{ (Output Current Setting)}}$$

3-7 If the connected load resistance is ***greater*** than "R_L" in the expression above, the OPS will operate in the ***voltage mode.*** For load resistances ***smaller*** than "R_L," the OPS will transfer into the ***current-limit mode.*** When operating in the ***current-limit mode,*** the OPS delivers stabilized current (stabilization $\approx$ 2% of I_o max) into the connected load. The CURRENT control, in this mode of operation, is set to the desired output current, while the VOLTAGE control is set to the compliance voltage which the load requires. The VOLTAGE control channel functions now as a voltage limiter. When operating in the ***voltage mode,*** the OPS delivers stabilized voltage (stabilization $\approx$ 0.01% of E_o max) into the connected load. The VOLTAGE control, in this mode of operation, is set to the desired output voltage, while the CURRENT control is set to the desired output current which the load requires. The current channel of the OPS functions now as a current limiter.

3-8 THE OPS AS A REMOTE CONTROLLED VOLTAGE SOURCE

3-9 REMOTE RESISTANCE CONTROL. To control the output voltage of the OPS by a remote resistance, the internal "Voltage Control" must be disconnected at the rear barrier terminals and an external control resistor must be substituted. The value of the external control resistor is proportional to the Control Current used and to the desired output voltage. It may be determined by using the programming equation:

$E_o = (E_r/R_r)\,(R_{vc})$ (Eq. 1), where: E_o = Output Voltage
E_r = Reference Voltage
R_r = Reference Resistor
R_{vc} = Voltage Control Resistor

3-10 Sometimes it is convenient to express the ratio E_r/R_r as a Control Current (I_b), since I_b is indeed derived from the internal reference potential (E_r), in series with an external reference resistor (R_r), so that $I_b = E_r/R_r$ (Eq. 2). Equation (1) can, therefore, be simplified to:

$$E_o = I_b R_{vc} \quad \text{(Eq. 3).}$$

3-11 These equations (1, 2, 3) may be used conveniently for all calculations involving component selection for programming the OPS in the voltage mode.

3-12 If the Control Current (I_b) is precisely calibrated (by making part of R_r adjustable, as shown in FIG. 3-3), the output voltage (E_o), according to (Eq. 1), is directly proportional to the value of R_{VC}. In addition, if the amplifier offset voltage is carefully "zeroed" by means of the provided internal control, the voltage channel of the OPS is calibrated and will yield an exact "programming ratio." If, for example, as in the OPS, 1 milliampere of Control Current (I_b) is chosen, according to Eq. (1), a programming ratio of 1000 ohms (R_{VC}) per volt of output (E_o) results, i.e., for each 1000 ohms of programming resistance, 1 volt of output (E_o) will be produced.

3-13 COMPONENT SELECTION. A sample calculation will demonstrate component selection:

A Model OPS 100–5M is to be used as a voltage source, adjustable from 0–100 volts. If we select the control (I_b) to be 1 milliampere, the maximum voltage control resistor is given by:

$$R_{VC} = \frac{E_o}{I_b} = \frac{100V}{1\ mA} = 100\ k\ ohms.$$

3-14 The voltage control resistor (R_{VC}) may be a motor-driven or manually operated rheostat, as shown in FIG. 3-3, it may be a precision resistance decade, or a relay controlled step-switch arrangement. Error sensing, as shown in FIG. 3-3, will compensate for load wire voltage drops up to 0.5 volts per wire. If error sensing is not desired, the sensing wires (from terminals 4 and 2 to the load) should be deleted and the links between terminals (3)–(4) and (1)–(2) must be closed.

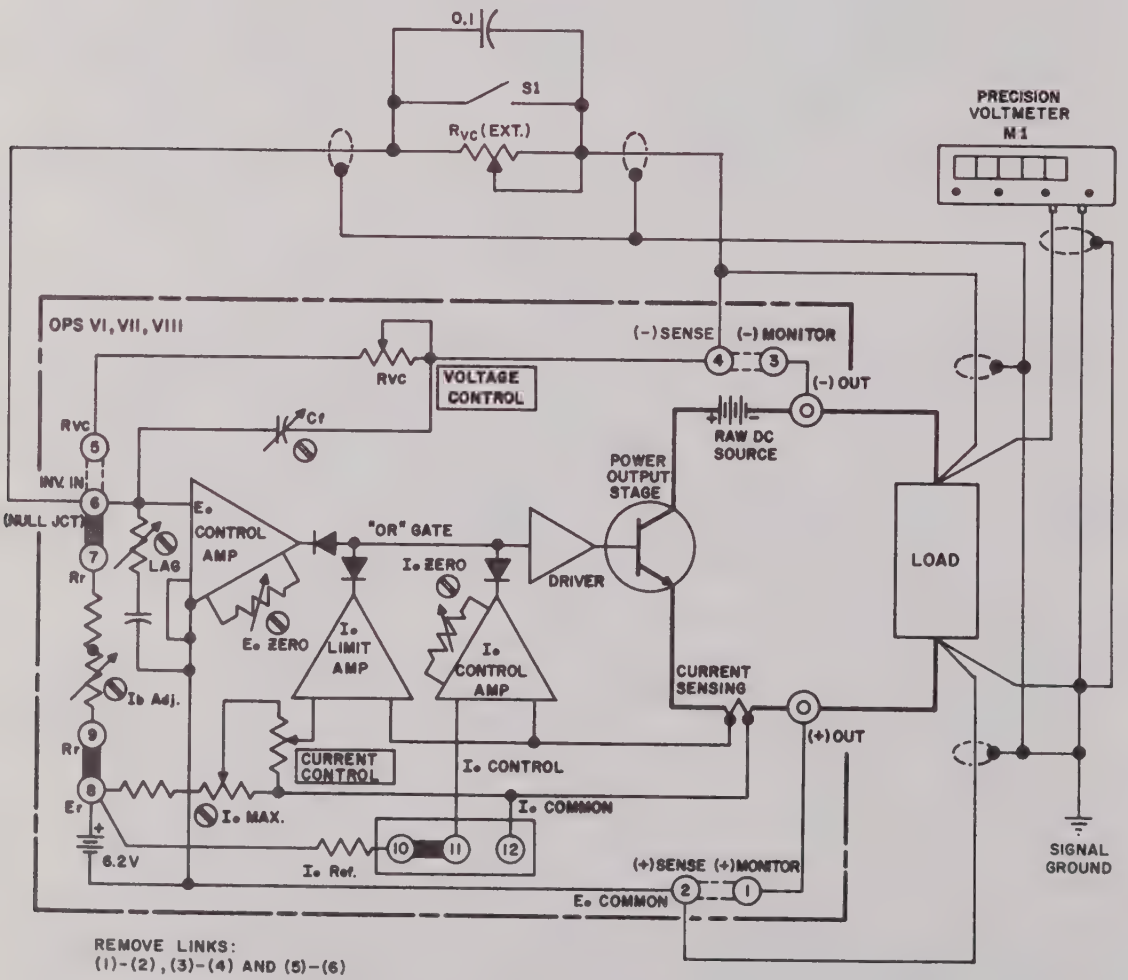


FIG. 3-3 CALIBRATION FOR EXACT PROGRAMMING RATIO.
EXTERNAL VOLTAGE CONTROL BY RESISTANCE.

3-15 CALIBRATION PROCEDURE. **NOTE: LOCATE ALL CALIBRATION CONTROLS BY REFERRING TO SECTION II, FIG. 2-1.**

a) Set up the calbration setup as shown in FIG. 3-3. The required external components are listed below:
   1) DIFFERENTIAL VOLTMETER, ***or*** 4-decade Digital Voltmeter (M1).
   2) SINGLE-POLE-SWITCH (S1).
   3) PRECISION RESISTOR (R_{VC}), select as shown in par. 3-13. For each ohm, one millivolt will appear at the output (with I_b = 1.0 mA).

b) ZERO CALIBRATION. Close "S1." Adjust ZERO control until the voltmeter (M1) reads exactly 0 volts.

c) I_b CALIBRATION. Open "S1." The output voltage on the voltmeter should read exactly: 1 milliampere times the value of R_{VC} in kilohms. Adjust the internal "I_b Adj." rheostat until this value is read out on M1.

d) Repeat adjustments in "b" and "c" as necessary, since calibration drift may take place during the time the OPS (and the voltmeter) reach thermal equilibrium.

3-16 SETTING THE OUTPUT CURRENT LIMIT CONTROL. ***Before each application,*** the front panel Current Limit Control should be adjusted just beyond the anticipated load current requirement. Proceed as follows:

a) Turn a-c power "off."

b) Connect a precision ammeter across the output terminals of the OPS.

c) Turn front panel Current Limit Control to its maximum ***counterclockwise*** position.

d) Turn a-c power "on." Observe external ammeter while slowly turning the Current Limit Control just beyond the required output current value.

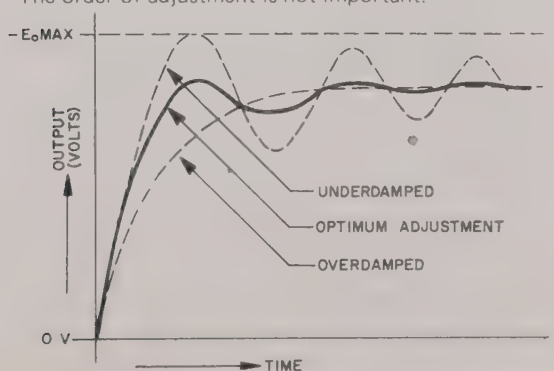
e) Disconnect the external ammeter and reconnect the load to the output of the OPS. This concludes the calibration.

3-17 DYNAMIC STABILITY ADJUSTMENTS. A careful check of the complete OPS Load system for dynamically stable operation should be part of each application.

3-18 The voltage channel of the OPS, when committed for voltage amplification or high speed resistance programming, represents an amplifying device with a relatively large bandwidth. Such devices are sensitive to the effects of load reactance, particularly capacitive reactance. The OPS is compensated for a controlled rolloff, with a constant phase shift. In order to maintain this controlled rolloff, it is necessary to confine the loading of the OPS to loads with nearly resistive properties. Excessive load reactance and/or input capacitance in combination with certain feedback impedances, may give rise to "ringing," "overshoot," or "oscillation" at the output of the OPS. Internal controls are provided in the OPS to compensate for a small range of load and input conditions. Lag networks at the input and output of the voltage channel and an adjustable trimmer capacitor across the feedback terminals of the OPS, may be individually adjusted for each load condition. These adjustments are accessible through the OPS cover and are marked LAG I, LAG II, LAG III and C_f respectively. (Refer to Section II, FIG. 2-1 for location.)

NOTE: The PROGRAMMING TIME CONSTANT (τ) is given by: $\tau \approx R_f C_f$, where "τ" represents the rise time of the OPS output response (following a step function input), from 0–63% of the OPS output voltage (Programming Speed). Selection of the value of R_f, and the adjustment of C_f will, therefore, determine the programming speed of the OPS in the linear operating region.

3-19 The dynamic characteristics of the OPS are optimized at the factory as follows:
The uncommitted channel is programmed with a square wave to its maximum power output into a resistive load. The output is observed with a high speed oscilloscope and the waveshape of the output square wave is optimized using the provided controls. (Refer to FIG. 3-4).
The order of adjustment is not important.



NOTE: **Increasing the feedback capacity (C_f) without simultaneously decreasing the feedback resistance (R_f) will increase the PROGRAMMING TIME CONSTANT ($T = R_f C_f$) and thereby slow down the OPS output response. The PROGRAMMING TIME CONSTANT is measured from zero to 63% of the output voltage response to a step-function input. (See also Section IV of this manual.)**

FIG. 3-4 SAMPLE OPS OUTPUT WAVEFORMS IN RESPONSE TO A SQUARE-WAVE INPUT SIGNAL.

3-20 Sometimes the factory adjusted optimum dynamic response may not be the best for a given application. In cases of persistent dynamic instability (oscillation) at the output, the LAG and C_f controls should be ***readjusted*** for the conditions of your particular application. In some cases, an additional capacitor across the feedback terminals (4)—(6) will establish stability, although at the cost of reduced bandwidth (i.e., programming speed). Note: The "programming speed" is expressed by the PROGRAMMING TIME CONSTANT: $\tau \approx R_f C_f$, where τ is the rise time from zero to 63% of the exponential output voltage response, following an input step function, and $R_f C_f$ is the product of the selected resistance/capacitance respectively. Investigate the load for excessive capacitance. Greater than specified load capacitances may introduce additional phase shift and the OPS may become unstable, especially with "follower" or "inverter" connections. The adjustment of the internal LAG and C_f controls may not help in cases of excessive load capacitance and may make the situation worse by increasing the net lag.

3-21 LOADS WITH EXCESSSIVE CAPACITANCE. One only solution, if such loads must be driven at higher frequencies, is to isolate them from the point at which the feedback is derived. (See FIG. 3-5 below.)

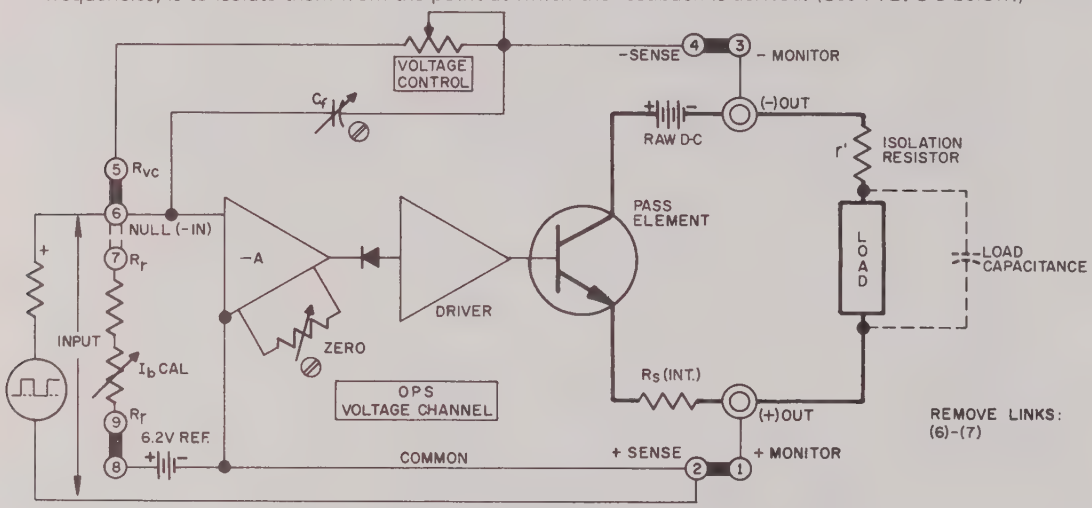


FIG. 3-5 ISOLATING A LOAD WITH EXCESSIVE CAPACITANCE.

3-22 The isolating resistor (r) should be only as large as is necessary to achieve stability, since the output impedance, is of course, increased by the amount of "r."

3-23 OUTPUT VOLTAGE CONTROL BY EXTERNAL SIGNAL VOLTAGE. In this application, the OPS functions as a unipolar power amplifier. The maximum peak-to-peak amplitude of the individual OPS model is equal to its rated d-c voltage output, and the average sine wave power into a resistive load is one-quarter of the rated d-c volt times the ampere product. The maximum, full power, sine wave frequency is given by:

$$f_{max} = \frac{S.R.}{\pi E_O \text{ max}} ,$$

where "S.R" is the slewing rate specified for the individual OPS model and "E_O max" is its rated maximum output voltage. For ***bipolar*** input waveforms, the OPS being a ***unipolar*** device, must be biased to accommodate the output swing. If this were not done, the OPS would reproduce only the negative going part of a bipolar input waveform. If the d-c output level of the OPS is preset to one-half its voltage range, however, it can handle the amplified bipolar waveform. (Refer to FIG. 3-6.)

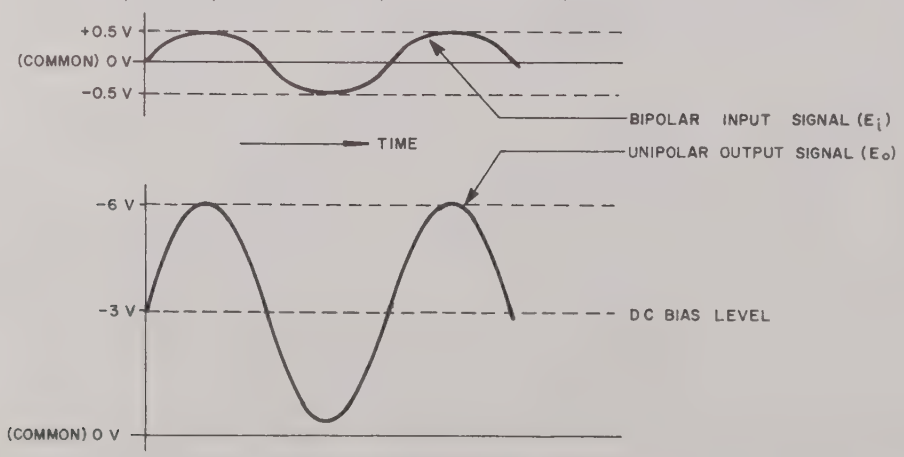


FIG. 3-6 INPUT/OUTPUT WAVEFORMS AND D-C BIAS.

3-24 COMPONENT SELECTION. Selection of external feedback and input resistors is based on the characteristics of the input source and on the desired circuit gain. The necessary values are calculated using the transfer function for an "ideal" operational amplifier in the inverting configuration:

$$E_o = E_i \frac{R_f}{R_i} \quad \text{(Eq. 4), where:} \quad \begin{aligned} E_o &= \text{Output Voltage of OPS} \\ E_i &= \text{Input Signal Voltage} \\ R_f &= \text{Feedback Resistor} \\ R_i &= \text{Input Resistor} \end{aligned}$$

3-25 If a bias is needed to accommodate a bipolar input signal, the necessary d-c control current may be derived from the internal reference source of the OPS. Then, the d-c control current and the bipolar signal are applied in a summing configuration to the inverting input of the OPS. The necessary circuit components for the d-c output are calculated using the programming equation given previously:

$$E_{o\,(d\text{-}c)} = I_b R_{vc} \quad \text{(Eq. 3).}$$

3-26 The following examples will demonstrate component selection using various input sources and specific OPS models.

EXAMPLE 1: A Model OPS 6-22M is to be programmed from a bipolar sine wave signal-generator able to provide 1 volt peak-to-peak into 600 ohms. An output amplitude of 6 volts is required. Since the input signal is bipolar, the d-c output voltage level of the OPS is set to the middle of its range (3.0 volt), so that the amplified input signal will be totally confined to the OPS output range: It will start from (−) 3.0 volt, go to (−) 6.0 volt, return to (−) 3.0 volt and go to the 0 volt and so on. (Refer to FIG. 3-6.) The resulting output wave will be a modulated d-c and will be ***unipolar,*** i.e., varying in ***one*** direction (negative) from zero.

3-27 To provide the necessary d-c bias at the output of the OPS, we make use of the internal d-c control current (I_b). Since we need a d-c output voltage (E_o) of (−) 3.0 volt, we can calculate R_{vc} by means of the output equation:

$$(-)\,E_{o\,(d\text{-}c)} = I_b R_{vc} \quad \text{(Eq. 3).}$$

The internal control current is calibrated to 1 milliampere, so that the necessary VOLTAGE control resistance (R_{vc} is equal to: $R_{vc} = E_o/I_b = 3V/1\ mA = 3\ k\ ohm$. Note: The front panel VOLTAGE control can be used for R_{vc} and set approximately to one-half its range.

3-28 Since the sine wave amplitude has to be 6 volts peak-to-peak, the a-c conditions are as follows:

$$\begin{aligned} E_{o\,(a\text{-}c)} &= 6V\ (p\text{-}p) \\ E_i &= 1V\ (p\text{-}p) \\ R_f &= 3.0\ k\ ohm\ (\text{calculated previously as "}R_{vc}\text{"}) \end{aligned}$$

3-29 The necessary gain (E_o/E_i) is therefore 6. Since the operational gain of the inverting input circuit used can also be expressed by the ratio of the feedback resistor (R_f) and the input resistor (R_i), the latter value can be calculated by: $R_f/R_i = 6$, $R_i = 3\ k\ ohms/6 = 500\ ohms$.

3-30 CALIBRATION. Connect all external components as shown in FIG. 3-7. Connect an oscilloscope and/or a digital voltmeter across the load. Turn OPS "on," and set output to zero by momentarily shorting the feedback terminals (4)—(6). Set to exact "zero" by means of the ZERO control. Remove short, set external GAIN CONTROL or the internal VOLTAGE CONTROL to 3000 ohms and adjust d-c output voltage to (−) 3.0 volts by means of the internal I_b ADJ. control. Turn SIGNAL GENERATOR "on" and adjust amplitude to 1 volt peak-to-peak. Observe output wave with an oscilloscope. The amplified sine wave should have an amplitude from 0 to (−) 6 volts, as the GAIN CONTROL is varied through its range. The full power frequency response of the OPS under these operating conditions will be from d-c to f_{max}, where:

$$f_{max} = \frac{\text{Slewing Rate}}{\pi E_{o\,max}} = \frac{50 \times 10^3\ V/sec\ \text{(As specified for OPS 6–22M in Section I)}}{6\pi V} \approx 2.65\ kHz.$$

NOTE: Increasing the input frequency above f_{max} will result in amplitude reduction and slope distortion.

3-31 As in any application, the front panel CURRENT control of the OPS should be set to the desired output current value. Refer to par. 3-16 for the adjustment procedure.

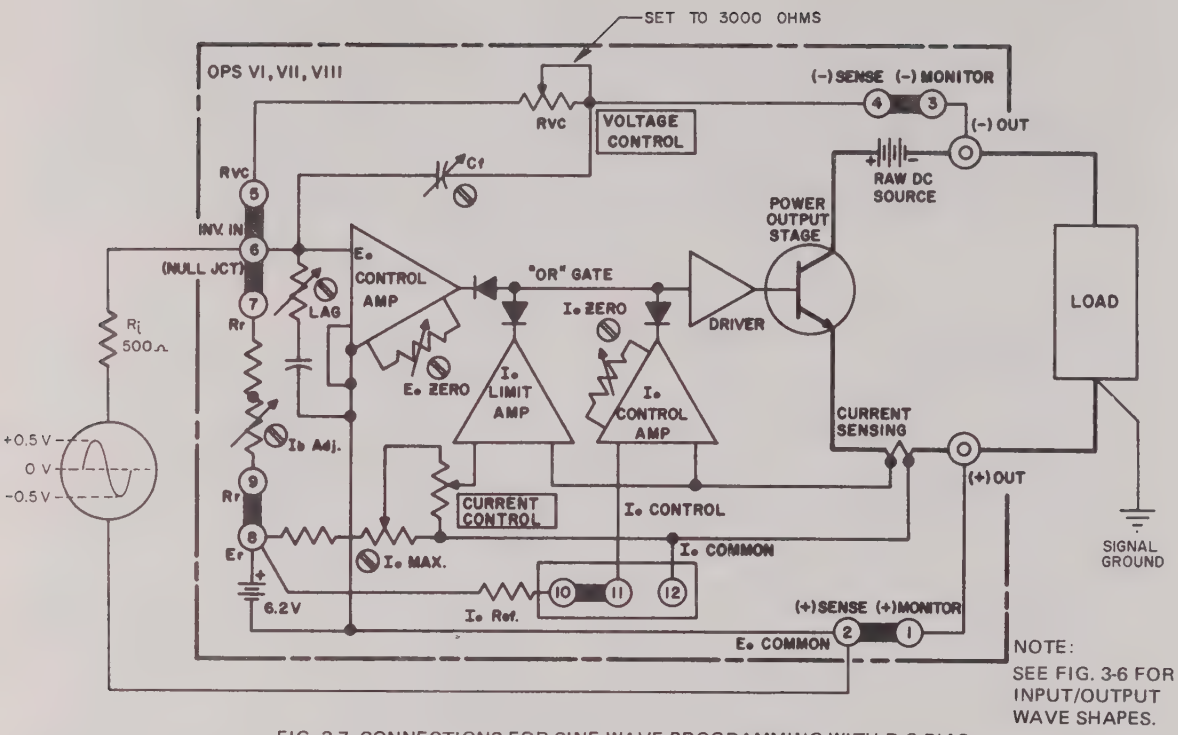


FIG. 3-7 CONNECTIONS FOR SINE WAVE PROGRAMMING WITH D-C BIAS.

3-32 EXAMPLE II: A Model OPS 15—12M is to be programmed to produce a triangular wave with an amplitude of 15 volts peak-to-peak. The input signal is provided by a Kepco Model FG—100A Function Generator, which can provide a direct, positive 1 milliampere drive. This makes it possible, to work without d-c bias and without an input resistor. The input/output waveforms and their phase relationship are shown in FIG. 3-8.

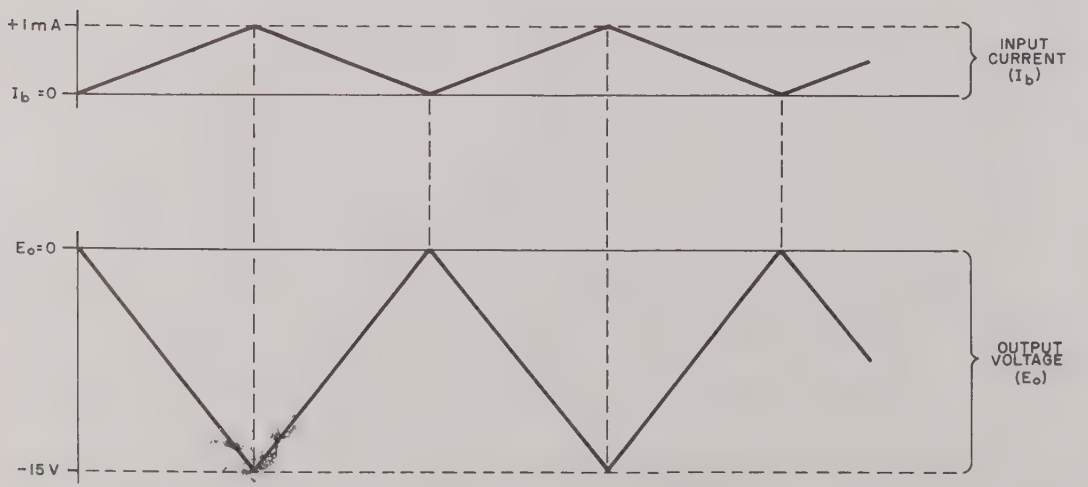


FIG. 3-8 OPS OUTPUT/INPUT WAVE SHAPES. INPUT SOURCE: POSITIVE-GOING TRIANGULAR WAVE GENERATOR.

3-33 Since I_b in this case is supplied directly from the generator, only the feedback resistor (R_f) must be calculated:

$$R_f = \frac{E_o}{I_b} = \frac{15V}{1\ mA} = 15\ k\ ohm.$$

NOTE: The internal VOLTAGE CONTROL (R_{VC}), set to its maximum clockwise position, can be used in place of an external feedback resistor (R_f).

The external components are now connected as shown in FIG. 3-9. Disconnect the internal d-c reference source (E_r) by opening jumper link (6)–(7).

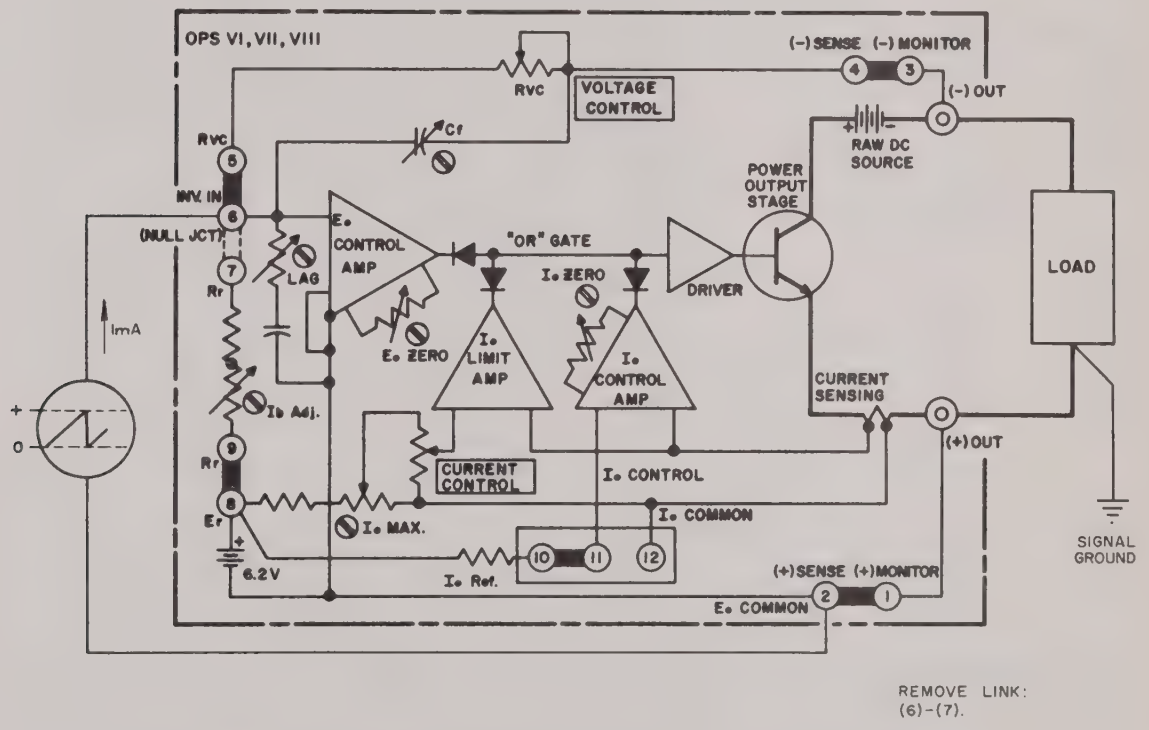


FIG. 3-9 CONNECTIONS FOR PROGRAMMING WITH THE KEPCO FG–100A FUNCTION GENERATOR.

3-34 CALIBRATION. Connect an oscilloscope and/or a digital voltmeter across the load, turn OPS and the function generator "on." Set OPS output to "zero" as follows:

a) Momentarily short the input leads to the OSCILLOSCOPE and set vertical sensitivity to about "5 mV/div." Set scope base line and mark its exact position. Reconnect scope leads across the load.

b) Short the feedback terminals (4)–(6) on the OPS. If the oscilloscope base line has changed from the previous marked position, correct with the OPS ZERO control.

c) Reset oscilloscope vertical sensitivity control to "2V/div." Remove short from the OPS feedback terminals (4)–(6). Adjust a convenient sweep speed on the control of the FG–100A and observe trace on the oscilloscope.

d) Adjust sweep amplitude on the FG–100A control until a peak-to-peak amplitude of 15 volts is observed on the oscilloscope.

3-35 Set OPS CURRENT CONTROL for desired load current. Refer to par. 3-16 for the adjustment procedure

3-36 EXAMPLE III: A Model OPS 36–8M is to be programmed to produce a 30 volt peak-to-peak square-wave output. The available input source is a square-wave generator with a positive "common" and a negative output, able to deliver a 2 volt signal at 1 milliampere. Since in this case, the input signal from the square-wave generator is of the "wrong" polarity, the OPS will be d-c biased to an output of 36 volts and programmed "down" from (-) 36 volts to (-) 6 volts, resulting in the desired output waveform and amplitude. Since ***either*** the negative ***or*** the positive output on the OPS may be grounded, this programming arrangement has proven satisfactory in cases where the input signal polarity cannot be changed readily. The expected input and output waveforms and phase relationships are illustrated in FIG. 3-10. NOTE: IF THE ***NEGATIVE*** OUTPUT IS TO BE GROUNDED, THE SIGNAL GENERATOR MUST BE CAPABLE OF BEING OPERATED "FLOATING" IN THIS APPLICATION.

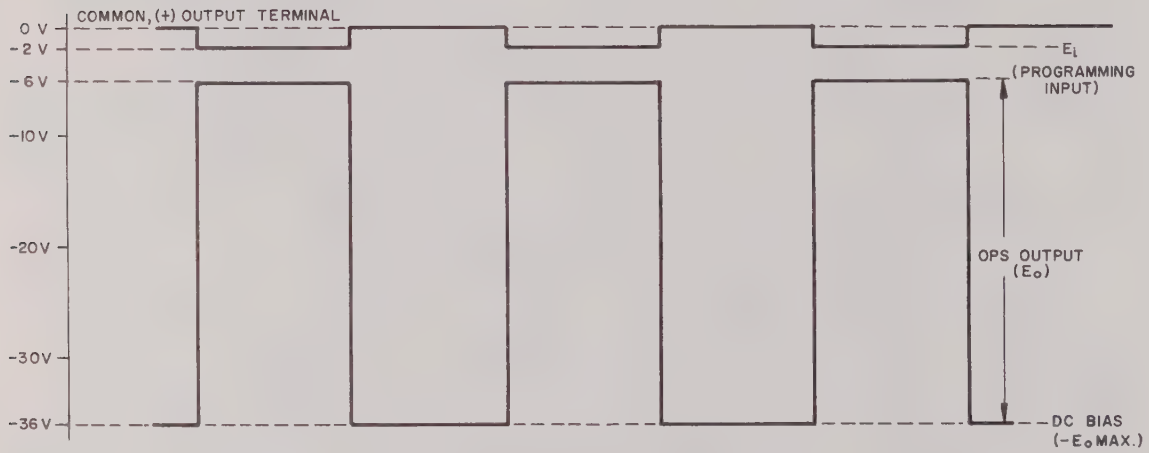


FIG. 3-10 INPUT/OUTPUT WAVEFORMS AND PHASE RELATIONSHIPS.

3-37 Considering first, the required d-c output (-36), and selecting 1 milliampere for the control current, we have:

$E_{o(d\text{-}c)}$ = (-) 36 volts (required d-c bias output).

I_b = 1 milliampere, provided from the internal OPS reference source.

R_{vc} (R_f) = E_o/I_b = 36V/1 mA = 36 k ohms for the voltage control (feedback) resistor. Either an external feedback resistor (R_f) can be chosen, or the internal OPS VOLTAGE CONTROL, set to 36 k ohms can be used in this application.

3-38 Considering the signal output:

E_o (signal) = 30 volts peak-to-peak

E_i = 2 volts peak-to-peak

R_f = 36 k ohms (as calculated previously for d-c)

The required gain E_o/E_i = 30V/2V = 15, so that the ratio of R_f/R_i must also equal 15:

$36\ k/R_i = 15$, $R_i \approx 2.4$ k ohm, to be externally connected in series with the generator.

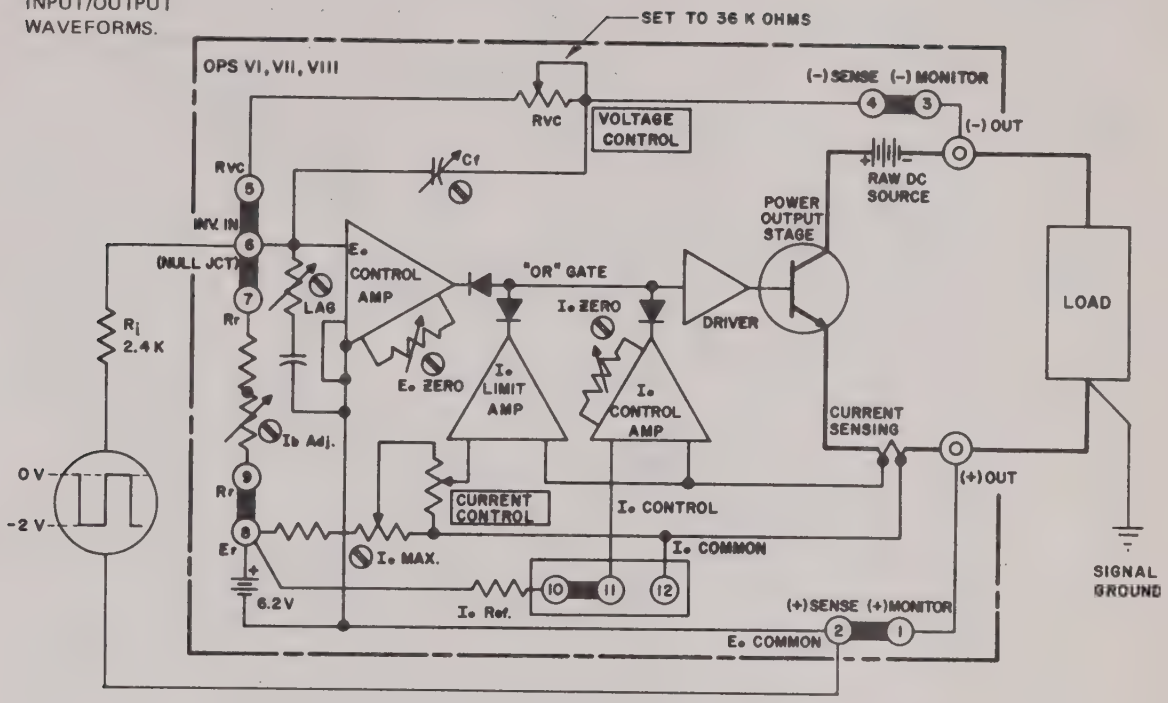


FIG. 3-11 CONNECTIONS FOR PROGRAMMING WITH NEGATIVE SQUARE WAVE INPUT.

3-39 CALIBRATION. Connect a suitable oscilloscope across the load. Connect external circuitry as shown in FIG. 3-11. Set OPS output to "zero" by momentarily shorting the feedback terminals (4)—(6) and correct by adjusting the OPS ZERO control. The square-wave output amplitude may be set by adjusting the generator input, or the OPS VOLTAGE control. The d-c bias output (-36V) may be set by adjusting the OPS I_b ADJ. control.

3-40 Set OPS CURRENT CONTROL for the desired load current. Refer to par. 3-16 for the adjustment procedure.

3-41 DYNAMIC ADJUSTMENTS. Observe the resulting waveform by means of the oscilloscope across the load. Adjust the provided internal controls (LAG and C_f) for maximum output stability under all operating conditions and/or optimum output waveshape. (Refer also to par. 3-17 for further details on dynamic stability.)

3-42 EXAMPLE IV: A Model OPS 25—10 is to be programmed to produce test voltages from zero to full output, commanded from a digital computer. The interface between the computer and the OPS Power Supply is a Kepco Model SN—3 Digital Programmer. Since the 0—10 volt output voltage from the Programmer serves as the input signal (E_i) for the OPS, it is converted to 0—1 millampere control current (I_b) by connecting a series resistance (R_i) to the OPS null junction or inverting input, while the internal OPS reference is disconnected. The control current (I_b) from the programmer is positive with reference to the "common," so that no d-c biasing is required.

3-43 The required feedback resistor is determined by the OPS output requirement (E_o = 25 volts) and the available control current (I_b = 1 mA) by:

$$R_f = E_o/I_b = 25V/1mA = 25 \text{ k ohms.}$$

NOTE: The internal OPS VOLTAGE CONTROL set to 25 k ohms can be used in place of an external feedback resistor (R_f).

The external components are now connected as illustrated in FIG. 3-12.

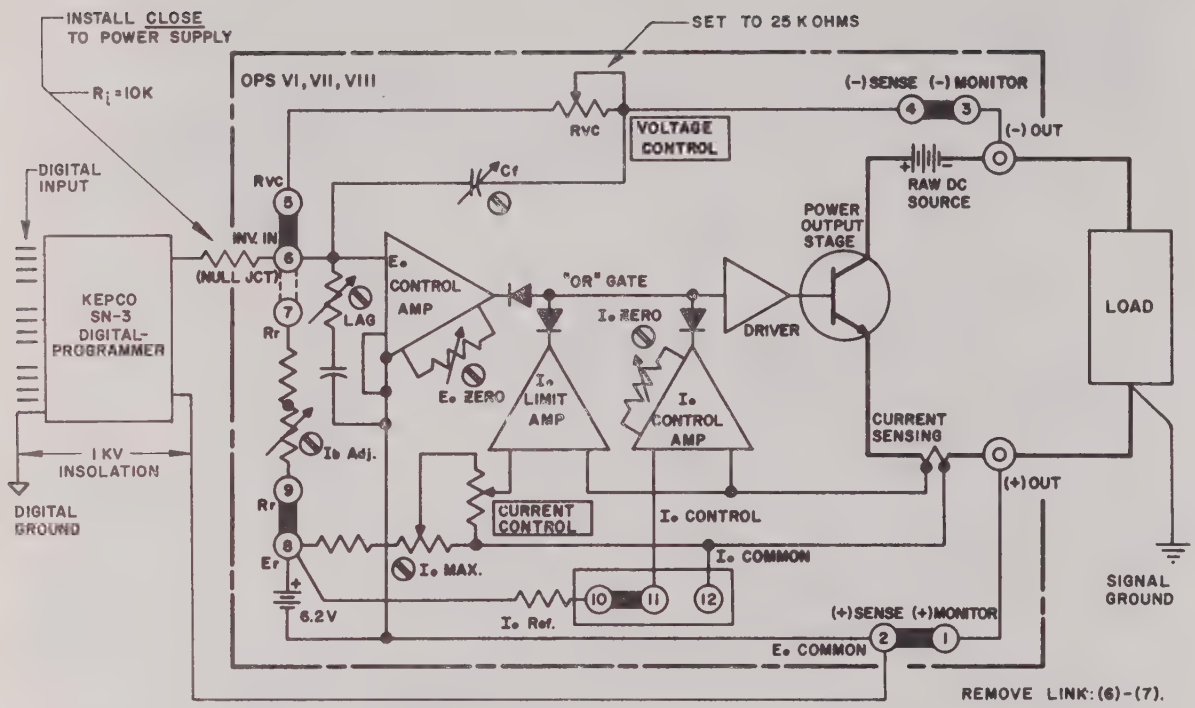


FIG. 3-12 CONNECTIONS FOR PROGRAMMING WITH THE SN CONVERTER.

3-44 CALIBRATION. Set OPS output to "zero" by momentarily shorting the feedback terminals (4)—(6) and correcting any offset by adjusting the OPS ZERO control. The maximum output from the OPS may be calibrated by programming "full scale" via the Programmer and either correcting the setting by means of the FULL SCALE adjustment on the Programmer, or by means of the OPS VOLTAGE control.

3-45 DYNAMIC ADJUSTMENTS. Observe the resulting waveform by means of a suitable oscilloscope across the load. Adjust the provided internal controls (LAG and C_f) for maximum output stability under all operating conditions, and/or for optimum output waveshape. (Refer also to par. 3-17 for further details on dynamic stability.)

3-46 THE OPS AS A PRECISION CURRENT SOURCE

3-47 The internal ***current limit circuit*** of the OPS with the front panel CURRENT control may be used as a current stabilizer for applications requiring about 2% stabilization. (Refer to par. 3-2d.) Improved current stabilization ($\approx$ 0.1%) may be achieved by remote control of the current limit circuit by means of an external potentiometer or a d-c control voltage. (Refer to par. 3-59.) For more demanding applications, requiring precision control and stabilization in order of 0.01%, an external sensing and control mode can be chosen, utilizing the ***voltage channel*** of the OPS. The CURRENT control at the front panel is set to the maximum anticipated output current and thereby serves as a "back-up" current limit.

CAUTION

3-48 Since the voltage channel is now used for current control, voltage limiting is now ***fixed*** to approximately 150% of the rated output voltage for the given OPS model. If the compliance voltage must be limited below this value, external means of limiting (such as zener diodes) must be provided across the feedback terminals (4)—(6) of the OPS.

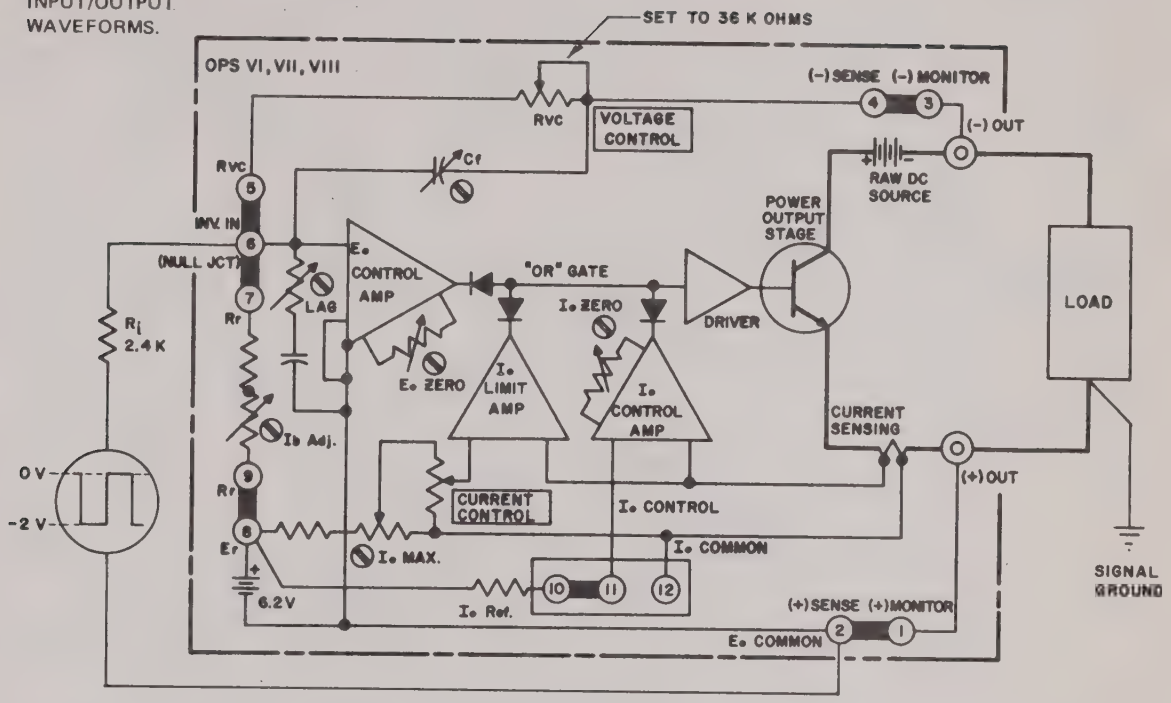


FIG. 3-11 CONNECTIONS FOR PROGRAMMING WITH NEGATIVE SQUARE WAVE INPUT.

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3-40 Set OPS CURRENT CONTROL for the desired load current. Refer to par. 3-16 for the adjustment procedure.

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3-43 The required feedback resistor is determined by the OPS output requirement (E_o = 25 volts) and the available control current (I_b = 1 mA) by:

$$R_f = E_o/I_b = 25V/1mA = 25 \text{ k ohms.}$$

NOTE: The internal OPS VOLTAGE CONTROL set to 25 k ohms can be used in place of an external feedback resistor (R_f).

The external components are now connected as illustrated in FIG. 3-12.

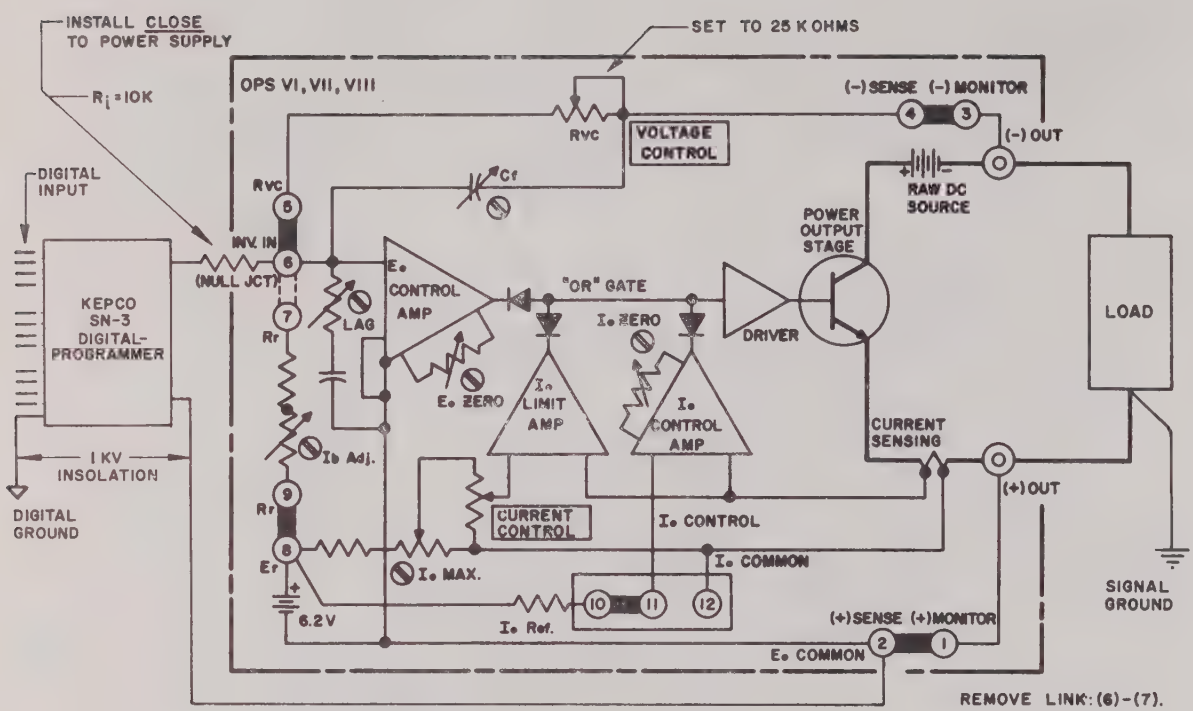

FIG. 3-12 CONNECTIONS FOR PROGRAMMING WITH THE SN CONVERTER.

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3-45 DYNAMIC ADJUSTMENTS. Observe the resulting waveform by means of a suitable oscilloscope across the load. Adjust the provided internal controls (LAG and C_f) for maximum output stability under all operating conditions, and/or for optimum output waveshape. (Refer also to par. 3-17 for further details on dynamic stability.)

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CAUTION

3-48 Since the voltage channel is now used for current control, voltage limiting is now ***fixed*** to approximately 150% of the rated output voltage for the given OPS model. If the compliance voltage must be limited below this value, external means of limiting (such as zener diodes) must be provided across the feedback terminals (4)—(6) of the OPS.

3-49 OUTPUT EQUATION. The transfer function for the OPS, with the voltage channel connected for external sensing and control of the output current, is derived from the equivalent diagram shown below: At $\epsilon = 0$ (amplifier input = zero):

$$I_b R_{cc} = (I_o - I_b) R_s \quad \text{and} \quad I_o = I_b \frac{R_{cc}}{R_s} + I_b \quad \text{(Eq. 1)}$$

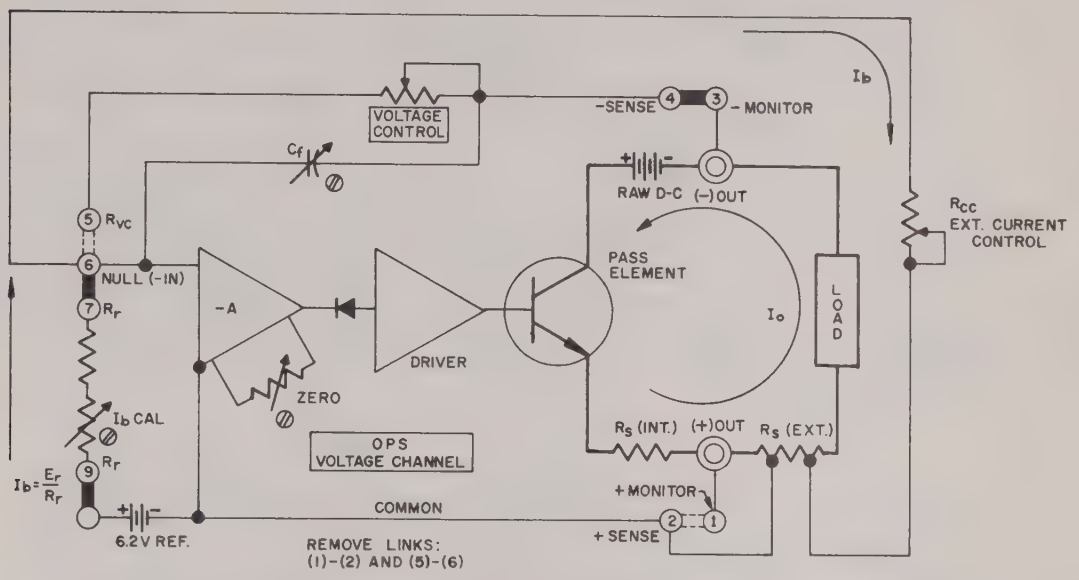


FIG. 3-13 EQUIVALENT DIAGRAM, OPS VOLTAGE CONTROL CHANNEL, CONNECTED FOR EXTERNAL SENSING AND CONTROL OF THE OUTPUT CURRENT.

3-50 As seen from the output equation (Eq. 1), the ***minimum*** output current (I_o), with the control resistance at zero ($R_{cc} = 0$) is limited to the value of the control current (I_b):

$$\left| I_o \text{ min} = I_b \right|_{R_{cc} = 0.}$$

3-51 To allow the output current to go to zero, "I_b" must be compensated for by means of a current ***equal to,*** but flowing in the ***opposite*** direction. This compensating current can be setup by adjusting the internal ZERO control of the OPS. ***After*** compensation, the output equation (Eq. 1) can be modified to:

$$I_o = I_b \frac{R_{cc}}{R_s}, \quad \text{(Eq. 2), which is used for all calculations.}$$

3-52 EXTERNAL CURRENT SENSING AND RESISTANCE CONTROL

3-53 COMPONENT SELECTION. The circuit shown in FIG. 3-13 is suitable for output currents from about 10 microamperes to the maximum rated output current for the given OPS model. The circuit components are selected as follows:

a) CURRENT SENSING RESISTOR (R_s). The value of the current sensing resistor (R_s) is chosen to develop a voltage drop (V_s) of 1 volt at the maximum desired output current (I_o max)

$$R_s = 1V/I_o \text{ max.}$$

The value of 1 volt for the sensing voltage (V_S) is somewhat arbitrary and the value of R_S may be therefore the closest standard resistance available. A wide departure from the recommended value should, however, be avoided because of the following considerations. While a large value of V_S (and therefore R_S) is desirable for a good signal/noise ratio, the sensing voltage sample is lost at the output and must be subtracted from the available rated compliance voltage. Also, a large sample voltage is not desirable in view of the power dissipation caused in the sensing resistor (R_S). Since all the load current is flowing through R_S and a high-gain amplifier circuit is connected across it, all extraneous changes (such as those caused by self-heating) must be kept as low as possible.

In view of these considerations, it has been found that the recommended value for V_S (1 volt) provides an acceptable signal/noise ratio for current control over a range of 1:50. If a wider range of current must be controlled, additional sensing resistors must be selected. All sensing resistors should be calculated to drop 1 volt at the maximum desired current.

b) CONTROL CURRENT (I_b). The internal zener voltage source (E_r = 6.2 volts nominal) can deliver required control current (I_b) via the internal reference resistor (R_r): $I_b = E_r/R_r$. The ***optimum*** value for I_b is 1 milliampere, since the zener source is temperature compensated for this current. Any value for I_b in the range from 10 microampere to 1.2 milliampere can, however, be chosen, by selecting the reference resistor accordingly. If optimum temperature performance is essential, a shunt load resistor (R_p) may be connected across the internal zener source to make up the difference between the control current used and the optimum 1 milliampere value. Suggested I_b and resistance values for various control ranges are given in Table 3-1. The control current values (I_b) may be precision adjusted by making part of R_r adjustable.

I_o RANGE	I_b	R_r	R_{cc}	R_s	SHUNT RESISTOR R_p
10 mA – 100 mA	1 mA	6.2 k ohms	1000 ohms	10 ohms	NONE
1 mA – 10 mA	100 μA	62 k ohms	10 k ohms	100 ohms	6 k ohms
100 μA – 1 mA	10 μA	620 k ohms	100 k ohms	1000 ohms	6 k ohms

TABLE 3-1 VALUES FOR EXTERNAL SENSING AND CONTROL CIRCUITS.

NOTE: The values in this table are calculated using the output equation (Eq. 2). They are valid for the "zeroed" OPS at a sensing voltage of 1 volt at the ***maximum*** desired output current (I_O).

c) CURRENT CONTROL RESISTANCE (R_{CC}). The current control resistance may be a fixed resistor, a step-controlled decade box or a rheostat. The resistors should be high quality components, with a temperature coefficient of 20 parts per million or lower. The value of R_{CC} is determined by substituting selected values (for I_O, I_b, and R_S) into the equation (Eq. 2) fiven in par. 3-51 and solving for R_{CC}. (Refer to Table 3-1 for tabulated values.)

3-54 EXAMPLE 1. To summarize the material presented in the previous paragraphs (3-46 to 3-53) a circuit for external sensing and resistance control is shown in FIG. 3-14 below. A OPS model is used to deliver stabilized output current from 0—10 milliampere into a fixed load. From the table of values (Table 3-1) we have:

I_b = 100 μA
R_S = 100 ohm
R_{CC} = 10 k ohm
R_r = 62 k ohm (use 55 k fixed, 10 k adjustable)
R_p = 6 k ohm

3-55 Connect all components as shown in FIG. 3-14. The sensing resistor (R_S) should be located as close to the power supply as possible. The leads connecting the control resistance (R_{CC}) must be shielded, with the shield (single-ended) connected to the signal ground. The signal ground point must be selected carefully to avoid ground-loops.

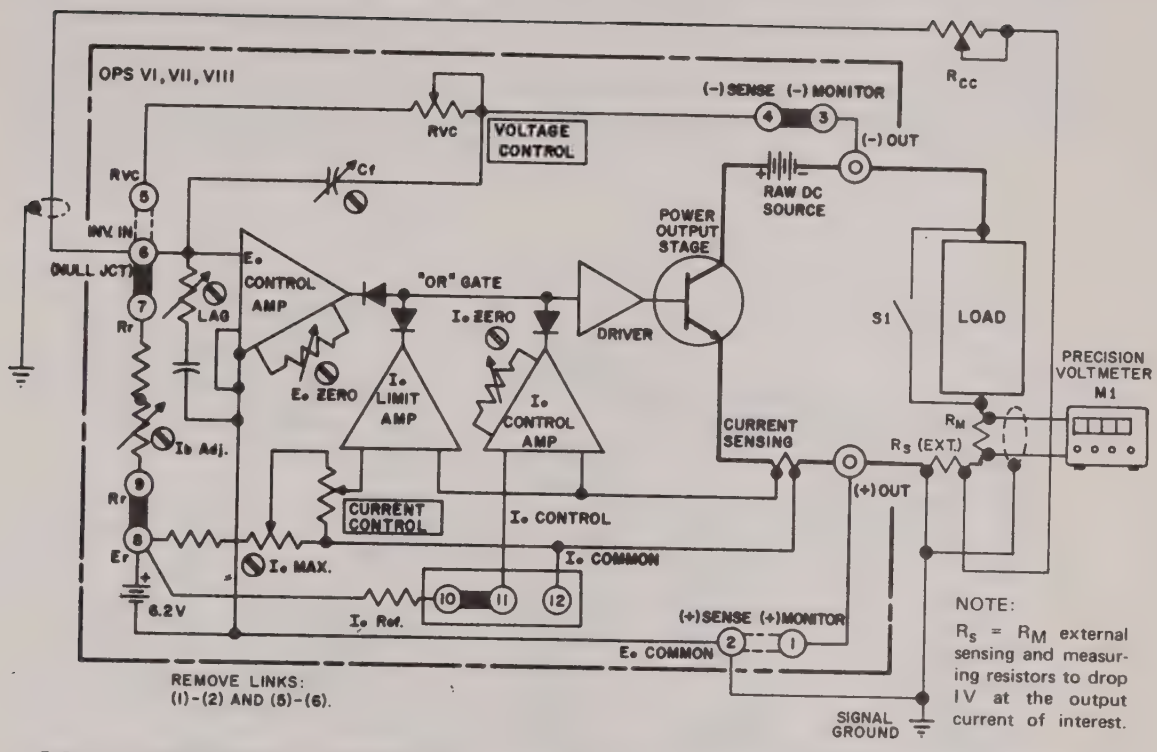


FIG. 3-14 CONNECTIONS FOR EXTERNAL SENSING AND RESISTANCE CONTROL OF THE OUTPUT CURRENT.

3-56 CALIBRATING THE OUTPUT

a) Turn OPS and precision voltmeter (M1) "on" and allow the circuit to reach thermal equilibrium. The output current (I_O) is proportional to the voltage across M1 and the value of the measuring resistor (R_M): $I_O = V_{M1}/R_M$.

b) Set the external CURRENT CONTROL to "zero ohms" (I_O minimum). If output current is not zero, correct by means of the "zero" adjustment in the OPS (E_O ZERO).

c) Set the external CURRENT CONTROL to its maximum resistance (I_O maximum). If output current is not maximum, correct by adjusting the OPS I_b ADJ. control.

d) Recheck "zero" adjustment by repeating "b."

3-57 OUTPUT MEASUREMENTS. Output effect measurements may be performed by using the setup shown in FIG. 3-14. For output effects due to a-c source changes, a means of varying the a-c source (variable transformer or "step" device) should be provided. For load effect measurements, the shorting switch (S1) is connected across the load. If the load is now shorted, or the a-c source varied, the deviation, (ΔV_{RM}) of the digital meter (M1) divided by the value of the measuring resistor (R_M) is an indication of the d-c stability of the output current. In percent:

$$\Delta I_O\,(\%) = \frac{\Delta V_{RM}/R_M}{I_O} \times 100\% = \frac{\Delta V_{RM}}{V_{RM}} \times 100\%.$$

3-58 OUTPUT RIPPLE AND NOISE. Output current ripple, as observed with an RMS reading meter or oscilloscope across R_M, must be converted into current units by dividing the RMS or peak-to-peak reading by the value of R_M. The ripple amplitude may often be greatly reduced by a capacitor across the sensing resistor (R_S). Since the major ripple component is the a-c source frequency, the capacitor must have a low impedance compared to R_S at this frequency. The capacitor will slow the response to load voltage changes in the OPS. A compromise between the desired response time and the ripple amplitude must, therefore, be made.

3-59 PROGRAMMING THE CURRENT CONTROL CHANNEL

3-60 The function of the current control channel in the OPS has been briefly discussed in par. 3-2d of this section. The control channel has been utilized, in previously described applications, as a current limiter, ***controlled locally*** by means of the built-in Current Control potentiometer. It can, however, be ***remotely programmed*** either to function as a current limiter, or as an independent, continuously adjustable current stabilizer.[1] The two basic methods of remotely controlling the current channel of the OPS are described in the following paragraphs.

3-61 OUTPUT CURRENT CONTROL BY POTENTIOMETER. In this control mode, the front panel CURRENT control is set to the ***maximum*** desired output current value (these controls serves as a "back-up" current limit), and a remote resistor network is connected to the OPS barrier-strip terminals. (Refer to FIG. 3-15.)

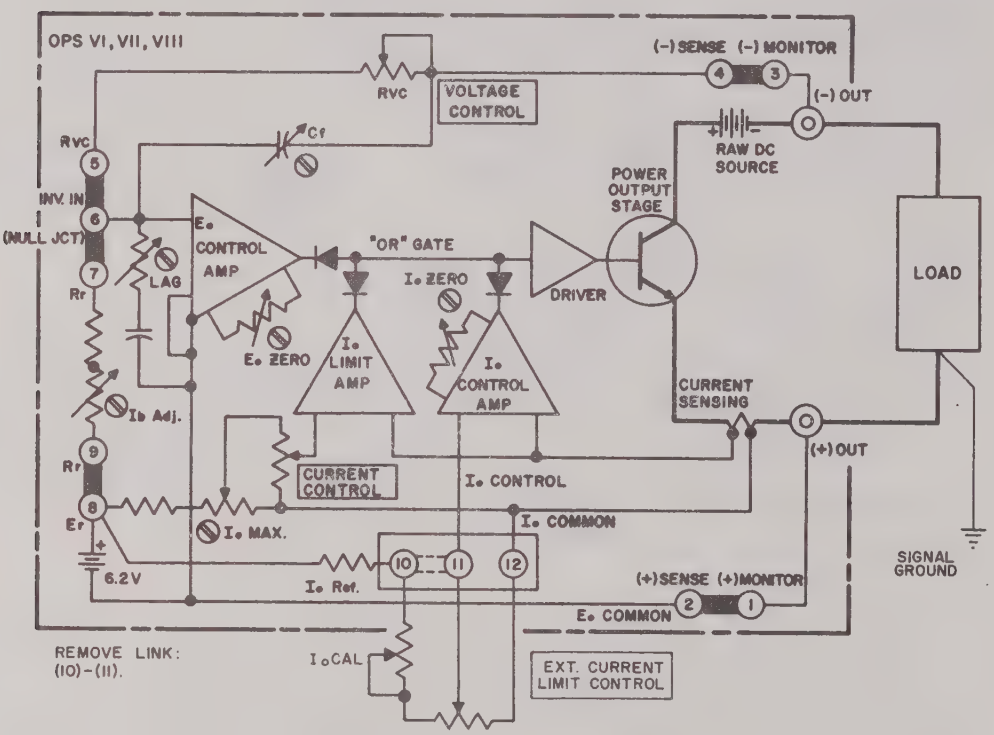


FIG. 3-15 CONNECTIONS FOR REMOTE OUTPUT CURRENT CONTROL BY POTENTIOMETER.

3-62 The voltage channel must be committed to either a voltage or amplifier mode of operation. The values of the feedback (or voltage control) resistor and input (or reference) resistors needed, are calculated as described in the applications for programming the voltage channel. (Refer to par. 3-8 for example.) Alternately, the internal VOLTAGE control and reference may be retained as shown in FIG. 3-15. Set output voltage control for the ***maximum*** required compliance (load) voltage.

3-63 For OPS models with output current rating ***below*** 5 amperes, the value for the external Current Limit Control potentiometer must be 2 k ohms. For OPS models with 5 amperes or greater output current rating, the external Current Limit Control is 1 k ohm. A small calibrating rheostat (I_O CAL. in FIG. 3-5) may be connected in series with the Current Limit Control. Its value is chosen such that the output current of the OPS can be calibrated to its maximum rated value, with the external Current Limit Control at its maximum resistance position. The low end of the output current range may be calibrated by adjusting the built-in I_O ZERO control. (See Section II, FIG. 2-1 for location.)

[1] Recommended for output currents from about 1 milliampere to I_O max. Stabilization is approximately 0.1%. Use the voltage channel with an external feedback circuit for control of output currents below 1 milliampere. (See par. 3-52.)

3-64 OUTPUT CURRENT CONTROL BY AN EXTERNAL CONTROL VOLTAGE. The output current of the OPS can be programmed by means of an external, adjustable d-c control voltage of 0 to 1 volt (models with output current ratings ***below*** 5 amperes) or of 0 to 0.5 volts (models with output current ratings of 5 amperes and above). The method of applying the programming voltage can be as simple as using a mercury battery with a potentiometer, or it can be a computer-controlled command with a Kepco SN programmer as the interface.

3-65 As shown in FIG. 3-16, the VOLTAGE channel of the OPS must be committed to either a voltage, or an amplifier mode of operation. The values of the feedback (or voltage control) and input (reference) resistances are calculated as described in previous applications for programming the uncommitted channel. Set the output voltage control for the ***maximum*** required compliance (load) voltage.

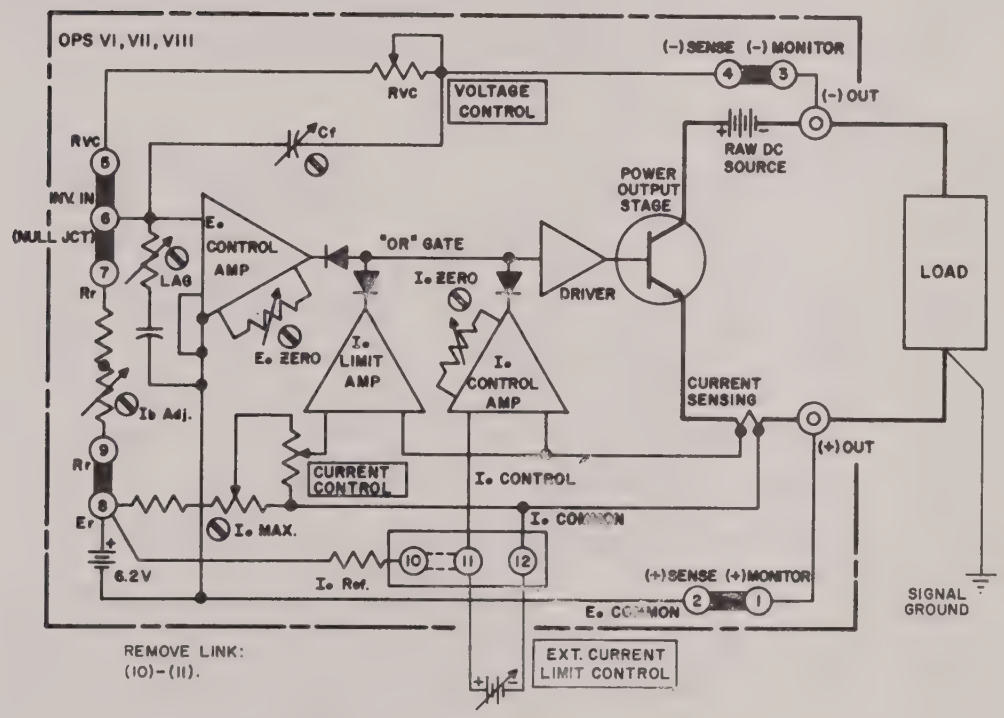


FIG. 3-16 CONNECTIONS FOR REMOTE OUTPUT CURRENT CONTROL BY A D-C VOLTAGE SOURCE.

NOTE: The scope of an instruction manual does not permit an elaborate treatment of all aspects of operational power supply programming. The concept of resistance programming, for example, can be extended to include control with other than the standard 1000 ohm per volt ratio, or "conductance" programming by varying the control current. Another interesting example would be resistance programming by means of Kepco's Digital Programming System (DPD/DPR). For further detailed information on these and other programming methods, or for information on ***your*** specific application, please contact the Kepco Applications Department, Flushing, New York.

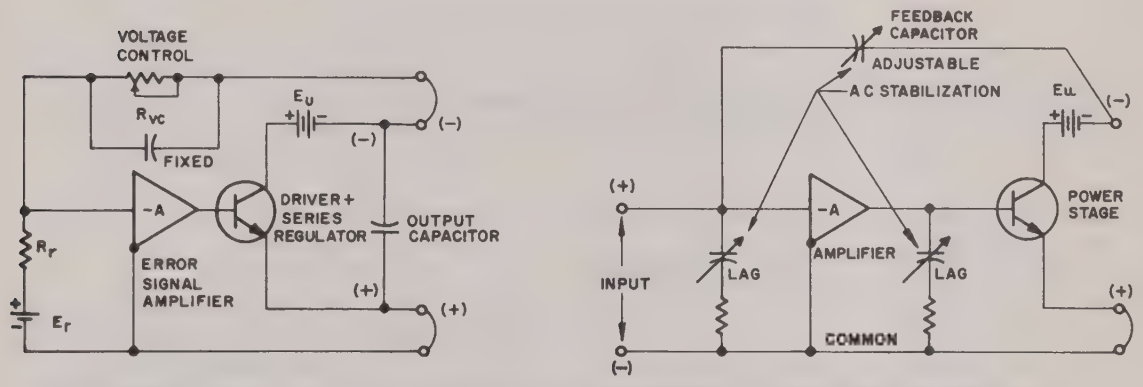
SECTION IV – THEORY OF OPERATION

4-1 GENERAL

4-2 A ***Standard Power Supply*** is not well suited for tasks requiring a fast output response. It is generally optimized as a ***Voltage Source*** and its bandwidth is deliberately restricted, mainly by means of a large output capacitor. The standard power supply is designed to approach the characteristics of an ideal voltage source: low output ripple, low source resistance and a large storage capability.

4-3 By contrast, an ***Operational Power Supply*** exhibits the characteristics deliberately surpressed in a standard power supply: wide bandwidth and fast output response. The wide-band characteristic is achieved by removing the large capacitor at the output and shaping the open-loop response by means of lag networks. The trade-offs which must be accepted are: higher output ripple and output impedance and restrictions on reactive loading.

4-4 An ***Operational Power Supply*** can, however, perform tasks which would be impossible for a standard supply: as a ***D-C Power Source,*** it can be programmed to provide high speed voltage or current level changes. As a ***Unipolar Power Amplifier,*** it can amplify unipolar or bipolar waveforms to power levels limited only by its own output ratings. As an ***Operational Amplifier*** it can serve as a summer, scaler or integrator, and can perform any other operational task. In addition, the Operational Power Supply, with its wide bandwidth and its fast response to load voltage changes, is ideally suited to function as a ***Stabilized Current Source.***



A) POWER SUPPLY

B) OPERATIONAL POWER SUPPLY/AMPLIFIER

FIG. 4-1 COMPARISON: STANDARD POWER SUPPLY WITH AN OPERATIONAL POWER SUPPLY.

4-5 OPERATIONAL POWER SUPPLY SPECIFICATIONS

4-6 GENERAL. The performance of Operational Power Supplies is described in terms of the following parameters:

1) D-C OFFSET VARIATIONS.
2) OPEN-LOOP GAIN (Specified at d-c).
3) MAXIMUM SLEWING RATE.
4) MAXIMUM SINE WAVE FREQUENCY (FULL POWER).
5) PROGRAMMING TIME CONSTANT.

4-7 Since there are no established standards to describe the behavior of Operational Power Supplies, the terms used by Kepco, Inc., are defined in the following paragraphs. The discussion includes the test circuitry used to establish the specifications, as well as notes on their application.

4-8 D-C OFFSET VARIATIONS. Any power supply, "standard" or "operational," consists of a comparison amplifier, a reference source and a power amplifier or series regulator section. (Refer to FIG. 4-1.) The effects of various external influences, such as time, temperature, load or a-c source variations upon the d-c output of ***any*** power supply are due to small variations at the input of the comparison amplifier. These small errors or "offset variations" are transferred to the output, amplified by a factor which depends on the gain (ratio of reference voltage to output voltage) and the value of the feedback resistor (voltage control resistor) at any given output level. Since a "standard" power supply has only a limited range of gain and feedback resistance,

the total "worst case" error can be specified ***directly*** as an ***output effect*** in response to the various ***Influence Quantities.*** In an operational power supply, however, the gain and the feedback resistor are selected by the user and may, therefore, vary over a much wider range. For this reason, the ***offset variations*** are specified for the power supply amplifier input. Once the user has selected the feedback components and the required gain for the application at hand, the output effects can be calculated by means of the ***error equation.***

4-9 As seen from FIG. 4-1, an operational power supply can be represented as an amplifier, driving a power stage in series with the raw d-c source. It can, therefore, be analyzed using operational amplifier terminology. The circuit shown in FIG. 4-2 is further simplified by including the power stage and the raw d-c source into the amplifier triangle. Adding an input source (E_i) with a series resistor (R_i) and a feedback resistor (R_f), a model of an "ideal" operational amplifier (inverting configuration) results, for which the following assumptions are made:

1) The offset current (I_{io}) at the input terminal (Null Junction) ***approaches*** zero ($I_{io} \rightarrow 0$).
2) The open-loop gain (A) ***approaches*** infinity ($A \rightarrow \infty$).
3) The input voltage (E_{io}) ***approaches*** zero, when the feedback loop is closed ($E_{io} \rightarrow 0$).

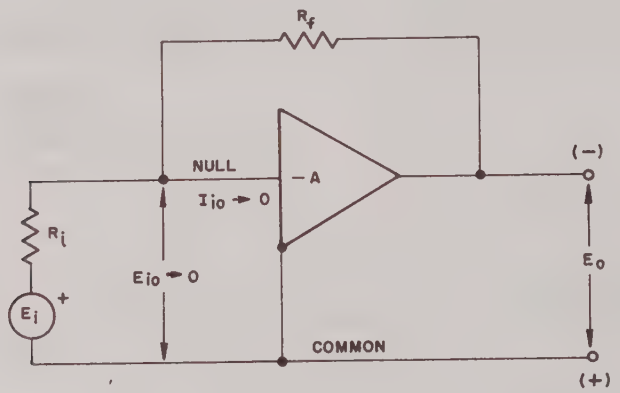


FIG. 4-2 MODEL OF IDEAL OPERATIONAL AMPLIFIER WITH FEEDBACK (INVERTING CONFIGURATION).

4-10 Refer to FIG. 4-2. If the input error voltage and current (E_{io}, I_{io}) are assumed to be zero, and that gain is infinite:

$$\frac{E_i}{R_i} = \frac{E_o}{R_f} ,$$

or in the more familiar form,

$$E_o = -E_i\left(\frac{R_f}{R_i}\right) \text{ (Eq. 2)},$$

where, the ratio R_f/R_i represents the closed-loop gain. Equation (2) thus becomes the transfer function for the operational amplifier in an inverting configuration. Although the expression (Eq. 2) was derived for the "ideal" case, it may be readily applied to the practical operational power supply circuit. The transfer function (Eq. 2) is, for example, extensively used to calculate the values for the input and feedback resistors, since the associated errors are negligible compared to standard component tolerances. These errors neglected in the "ideal" model must, however, be considered in evaluating the d-c performance at the output of an actual operational power supply.

4-11 AMPLIFIER OFFSETS. In developing the ideal amplifier model, we tacitly assumed the null junction voltage and current to be zero causing the "ideal" equation (2) to be valid. In reality, however, nonidealities do exist at the null junction or input terminal of the amplifier. These errors are of the form of an offset voltage (E_{io}) and an offset current (I_{io}). The modified version of the amplifier model can be shown with these error sources as in FIG. 4-3.

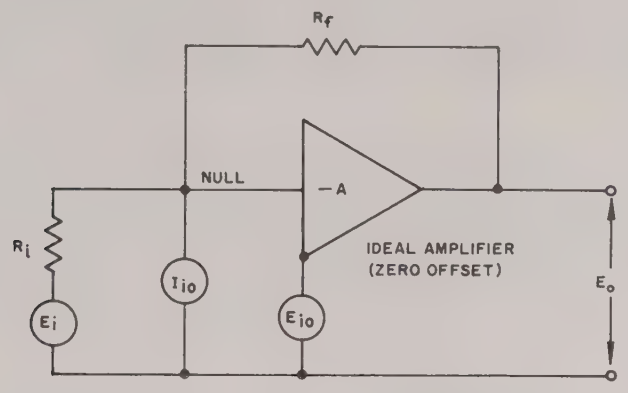


FIG. 4-3 AMPLIFIER WITH INPUT OFFSET SOURCES.

4-12 Although the INITIAL values of both offsets (E_{io}, I_{io}) may be cancelled by compensating sources of opposite polarity,[1] the VARIATIONS of the offsets (ΔE_{io}, ΔI_{io}) and the variation of the internal reference voltage (ΔE_i) with a-c input source, d-c load, temperature, and time changes ***do*** exist at the amplifier input and are specified as shown in the table (Table 4-1).

INFLUENCE QUANTITY	OFFSET VARIATIONS ΔE_{io}	OFFSET VARIATIONS ΔI_{io}	REFERENCE (6.2V ±5% NOMINAL) VARIATIONS
A-C INPUT SOURCE: (105 to 125V *or* 210 to 250V)	<10 μV	<2 nA	0.0001%
LOAD: No load to full load	<200 μV	<5 nA	NOT APPLICABLE
TIME: 8 hrs. (Drift)	<20 μV	<2 nA	0.005%
TEMPERATURE: Per °C	<20 μV	<5 nA	0.005%

TABLE 4-1 TYPICAL OFFSET SPECIFICATIONS FOR OPERATIONAL POWER SUPPLIES.

4-13 For a "worst case" analysis of the effects these tabulated errors have at the output of the operational power supply, their algebraic sum can be expressed by the "Error Equation" (Eq. 3)

$$\Delta E_o = \pm\Delta E_i\,(R_f/R_i) \pm \Delta E_{io}\,(1 + R_f/R_i) \pm \Delta I_{io}\,R_f$$

WORST CASE TOTAL OUTPUT EFFECT	OUTPUT EFFECT DUE TO VARIATIONS IN REFERENCE VOLTAGE	OUTPUT EFFECT DUE TO OFFSET VOLTAGE VARIATIONS	OUTPUT EFFECT DUE TO OFFSET VOLTAGE VARIATIONS

NOTE: Changes in R_f and R_i as a function of time and temperature are neglected in the above equation. In practical applications, R_f and R_i should have low, matched temperature coefficients, for optimum d-c stability.

[1] OPS Power Supplies have a built-in control, to zero E_{io} (ZERO control). No control is provided for zeroing I_{io}, since its value is not significant for most applications. I_{io} may be zeroed, however, (for very critical d-c applications with large feedback resistors) using an external nulling circuit. Please contact KEPCO'S Application Department for further information.

4-14 An inspection of the individual terms of the error equation (Eq. 3) re-emphasizes the previously discussed reasons for specifying all error voltages separately at the ***input*** to the power supply amplifier: The magnitude of the ***output effects*** caused by the individual errors (ΔE_i, ΔE_{io}, ΔI_{io}) depend on the ***ratio*** of the feedback and input resistor (R_f/R_i = closed-loop gain) and on the ***value*** of the feedback resistor (R_f). Since the gain and the input/feedback components are selected by the user, the total output effect (ΔE_o) must be calculated for each application by means of the error equation. The separation of the terms in the error equation allows the analysis of the contribution of each error to the total output effect and permits component selection so as to minimize the total effect.

4-15 A practical example should illustrate the use of the derived equations and the offset specifications: A Model OPS 75–8M is used as a d-c voltage source in an application requiring 62 volts into a constant load. The available a-c source voltage is stable, but the temperature in the operating environment changes over a range of 10°C. The effect of this temperature change on the output voltage of the OPS is to be predicted.

In this application, the internal reference voltage (E_r = 6.2V nominal) may be used in series with the internal reference resistor (R_r) to produce the required 1 milliampere control current (I_b). If these predetermined values are substituted into the "ideal" transfer function, the value of the feedback resistor for 62 volts output is given by:

$$R_f = E_o\,(R_i/E_r) = \frac{62V \times 6.2\,k}{6.2V} = 62\text{ k ohms,}$$

(NOTE: The front panel VOLTAGE CONTROL can be left connected and set to this value.)

and the closed-loop gain (R_f/R_i) equals 62 k/6.2 k = 10.

Inserting the selected values for R_i and R_f and the offset specifications (from Table 4-1) into the error equation (Eq. 3), the output effect due to the anticipated temperature change can be predicted:

$$\begin{aligned}\Delta E_o &= 310\,\mu V\,(10) + 20\,\mu V\,(1+10) + 5\text{ nA}\,(6.2 \times 10^4\ \Omega)\\ &= 3.10\text{ mV} + 0.22\text{ mV} + 0.31\text{ mV} = 3.63\text{ mV per °C.}\end{aligned}$$

OUTPUT EFFECT DUE TO REFERENCE VARIATION	OUTPUT EFFECT DUE TO OFFSET VOLTAGE VARIATION	OUTPUT EFFECT DUE TO OFFSET CURRENT VARIATION

or 36.3 mV output voltage change over the 10°C temperature range. It should be noted, that the calculated total output effect (ΔE_o) represents a "worst case" prediction, assuming all error terms are positive. In practice, this is not the case. A TYPICAL value for the above example would be considerably smaller, as actual measurements on large numbers of operational power supplies have shown.

4-16 OPEN-LOOP GAIN. In the "ideal" transfer function for the operational power supply (Eq. 2), the open-loop gain (A) was assumed to be infinite. In reality, however, it is finite and in the order of 10^5 to 10^7 (volts per volts). Although operational power supplies are seldom used in an open-loop configuration, the open-loop gain (A) is of interest since it provides a measure of the possible programming accuracy. Finite open-loop gain introduces a "gain error" into the "ideal" transfer function (Eq. 2), which limits the absolute closed-loop accuracy and gain linearity. While the absolute closed-loop ***accuracy*** can be "calibrated away" by adjusting the feedback resistor, the ***gain linearity*** cannot be corrected. The specified open-loop gain (A), specified at d-c, is a measure of that linearity. To illustrate the significance of the open-loop gain, consider the modified transfer function for the operational power supply in the inverting configuration:

$$\frac{E_o}{E_i} = \frac{(R_f/R_i)}{1 + \dfrac{1}{A\beta}}\ ,\quad \text{(Eq. 4),}$$

where the "ideal" closed-loop gain ($E_o/E_i = R_f/R_i$) is modified by the error term $1/A\beta$, where A is the open-loop gain, and β represents the feedback ratio (R_i/R_f) (Approximately).

4-17 Assuming that the resistors (R_f, R_i) do not contribute to the gain error, consider an application where:

Specified Open-Loop Gain $(A)_{d\text{-}c} = 10^6$ volts/volt.

Ideal Closed-Loop Gain $(R_f/R_i) = 10^2$.

The gain (linearity) error, due to finite open-loop gain, in this case equals: $\dfrac{1}{A\left(\dfrac{R_i}{R_f}\right)} = 1/10^4$, or 0.01%.

4-18 DYNAMIC SPECIFICATIONS

4-19 GENERAL. The dynamic output behavior of the operational power supply can be described by two parameters: PROGRAMMING TIME CONSTANT and the MAXIMUM SLEWING RATE. The first describes the output response in the linear region while the other represents the output response to overdriven or forced input signals in the nonlinear region.

4-20 *PROGRAMMING TIME CONSTANT. The PROGRAMMING TIME CONSTANT expresses the "Programming Speed" in the linear operating region of the OPS output characteristic. It is given by:* $\tau \approx R_f \times C_f$, where R_f and C_f are the selected feedback components, and "τ" is the rise time, from 0 to 63% on the exponential output voltage response to an input step function.

4-21 The "programming time constant" (τ) can readily be translated into the frequency domain, thus yielding the upper "−3 dB frequency;" i.e., the highest sine wave frequency the operational power supply output can reproduce in its linear region. Since the programming time constant (τ) represents the rise time of the output voltage (0–63% E_O), it is inversely proportional to the upper −3 dB frequency (f_2):

$$t_r\ (0\text{–}63\%) = \tau = \frac{1}{\omega_2} = \frac{1}{2\pi f_2} = \frac{0.16}{f_2}$$

If, for example, $\tau = 100\ \mu$sec., $f_2 = 1.6$ kHz.

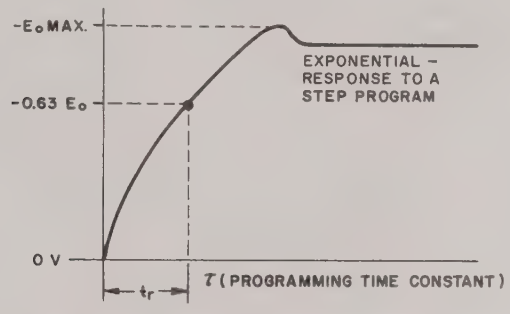


FIG. 4-4 DEFINITION OF THE PROGRAMMING TIME CONSTANT.

4-22 *MAXIMUM SLEWING RATE. The maximum slewing rate is the fastest time rate of change of which the operational power supply is capable.* The slewing rate is specified with the output fully loaded and measured as the output response to an input step function. As the exponential response to a step-input (such as a square wave, for example) is displayed on an oscilloscope, a slight increase in input amplitude will make rate limiting evident on the rising portion of the output waveform. (See FIG. 4-5).

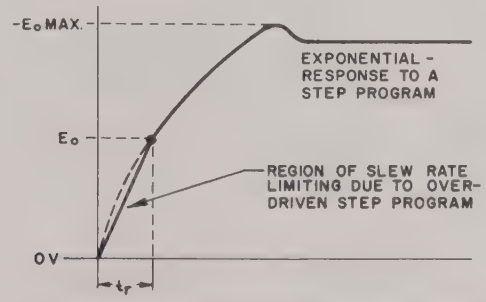


FIG. 4-5 DEFINITION OF MAXIMUM SLEWING RATE.

4-23 If a further increase of the driving signal amplitude does not produce a further change in the (E_O/t_r) slope of the displayed output response, the operational power supply is responding with the maximum slewing rate. The ratio E_O/t_r is measured over any convenient scale and the result is expressed in volts per microsecond.

4-24 If the input driving signal is a sinusoidal waveform instead of a step-function, the output waveform from the operational power supply is also a sinusoid. The maximum sine wave frequency which can produce the full output voltage (regardless of gain) is limited by the maximum slewing rate. The MAXIMUM SLEWING RATE and the FULL POWER SINE WAVE FREQUENCY (f_{max}) are related by the equation:

$$\text{SLEWING RATE} = \pi\, f_{max}\, E_{p\text{-}p}$$

where "$E_{p\text{-}p}$" represents the peak-to-peak output voltage of the operational power supply. The FULL POWER SINE WAVE FREQUENCY is specified for the frequency, where 5% total harmonic distortion occurs.

4-25 SIMPLIFIED DIAGRAM DISCUSSION (Refer to FIG. 4-6)

4-26 The POWER TRANSFORMER and the AUXILIARY TRANSFORMER convert the a-c source voltage to the levels required to produce the d-c operating potentials for the MAIN RAW D-C SUPPLY and the AUXILIARY D-C SUPPLIES. The MAIN RAW D-C SUPPLY is connected in series with the POWER OUTPUT STAGE, the CURRENT SENSING RESISTOR and the (±) OUTPUT terminals. The output level of the OPS is controlled by varying the series impedance of the POWER OUTPUT STAGE. The necessary drive to affect this control is provided by the DRIVER STAGE, which in turn receives its drive either from the VOLTAGE MODE or from one of the CURRENT MODE AMPLIFIERS (I_O CONT. INTERNAL AND I_O CONT. EXTERNAL.)

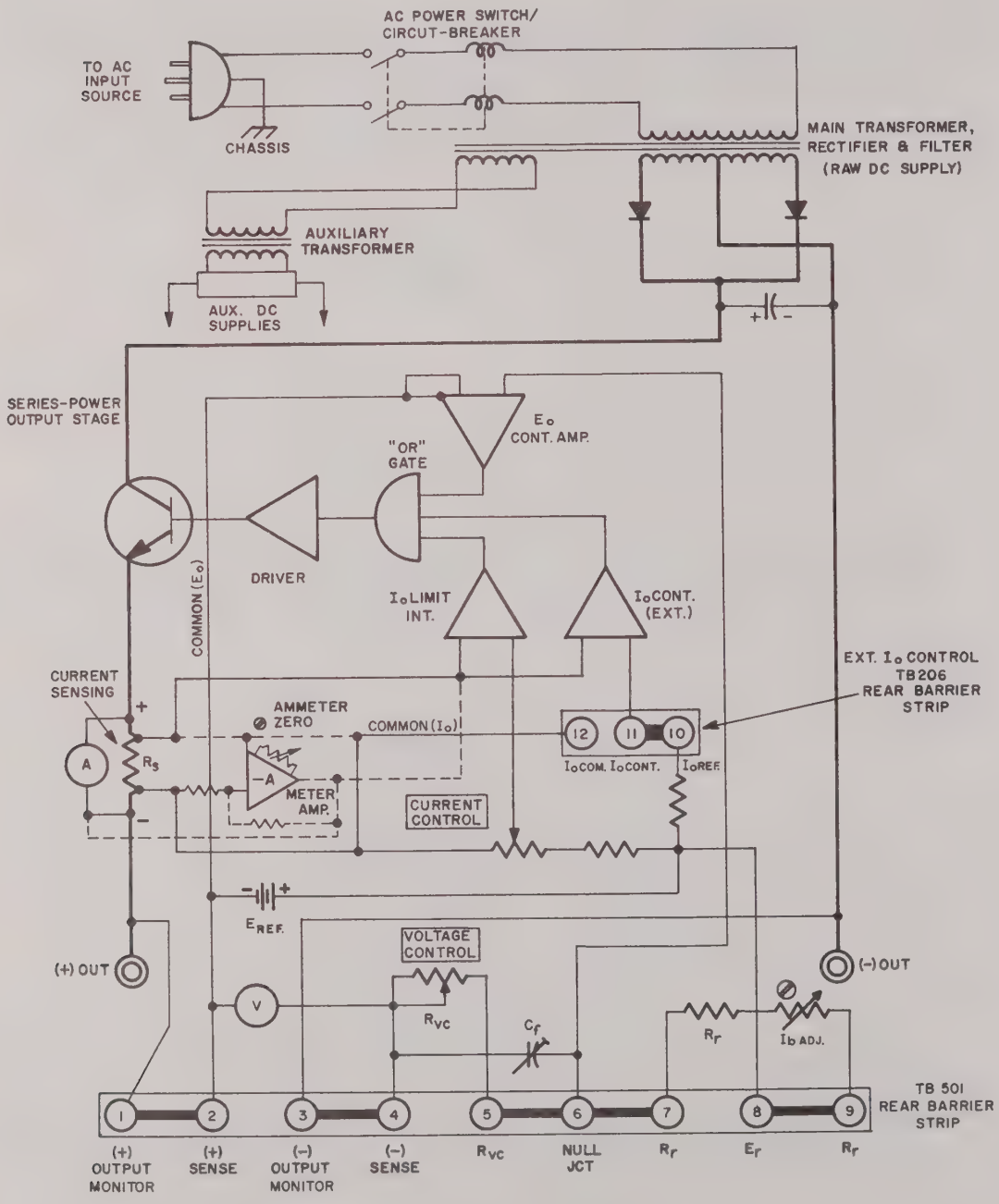


FIG. 4-6 SIMPLIFIED DIAGRAM, KEPCO OPS GROUPS VI, VII, VIII.

NOTE: The METER AMPLIFIER and its associated circuitry is used in the Model OPS 6–90M only. The meter amplifier boosts the sensing voltage across R_S to 1 volt.

4-27 If the OPS is used with the internally provided d-c reference source (E_r) and with internal feedback (VOLTAGE CONTROL) and reference resistors (R_r, I_b Adj.) connected as shown in FIG. 4-6, it functions as a d-c source delivering stabilized output voltage or current to the load. The operating mode ("voltage" or "current") is determined by the load resistance and by the setting of the VOLTAGE CONTROL and the OUTPUT CURRENT LIMIT CONTROL. If, in FIG. 4-7, "E_o" (voltage) and "I_o" (current) represent the respective settings of the output controls, the "crossover" resistance (R_{LX}) is given by Ohm's Law:

$$R_{LX} = E_o/I_o.$$

4-28 Any load resistance, ***smaller*** than R_{LX} (as, for example, R_{LI} in FIG. 4-7) will transfer the OPS into the "Current Mode." With any load resistance ***larger*** than R_{LX} (as, for example, R_{LV} in FIG. 4-7), the OPS will operate in the "Voltage Mode."

4-29 Operating as a d-c source (as shown in FIG. 4-6), the OPS output voltage and current are constantly monitored and compared to the internal temperature-compensated REFERENCE SOURCE. The VOLTAGE-MODE and CURRENT-MODE AMPLIFIERS operate as "Error-Signal Amplifiers," and at balance, the settings of the output controls and the value of the load resistance establish a given operating point on the output characteristic, as described previously. A change in either output control setting, or an external influence on the set output quantities (change in load, variations in a-c source voltage) are interpreted by the OPS sensing circuits as "Error Signals." Depending on the prevailing operating mode of the OPS, the "error signal" is amplified by either the VOLTAGE-MODE or one of the CURRENT-MODE AMPLIFIERS. The amplified error signal is presented to the OR–GATE, which only passes the most negative signal, so that only ***one*** of the amplifiers can be in control at any one time. Once the amplified error signal is passed by the OR–GATE, it becomes a "control signal" which, amplified by the DRIVER STAGE, is applied to the base of the transistors in the POWER OUTPUT STAGE. The power transistors in this stage change their series impedance in response to the control signal from the DRIVER STAGE. The control signal was derived from the "error signal" and is, therefore, proportional to the original output variation of the OPS. The resulting series impedance change in the POWER OUTPUT STAGE is, therefore, exactly inversely proportional to the original output variation, so that the OPS output is returned to the original value and thereby stabilized.

4-30 If the OPS is operated as a (unipolar) power amplifier, the INVERTING INPUT of the VOLTAGE-MODE AMPLIFIER is disconnected from the internal d-c reference source. The OPS output responds now to control signals applied to the INVERTING INPUT (Null Junction) with reference to the COMMON (+ SENSE) terminal. The gain in these applications is directly proportional to the ratio of the input resistor (R_i, connected to the INVERTING INPUT in series with the control signal) and the feedback resistor (***either*** the internal VOLTAGE CONTROL, or an external resistor connected from TB501–4 to TB501–6). The output of the OPS is "unipolar," varying in a single direction. The current limit circuit in this application is either locally controlled by setting the CURRENT CONTROL to the maximum desired output current, or by externally programming the I_O CONT. EXTERNAL amplifier.

4-31 The current limit may be remotely programmed either by an external potentiometer, or by an external control voltage. Directions for remote control are given in Section III of this manual.

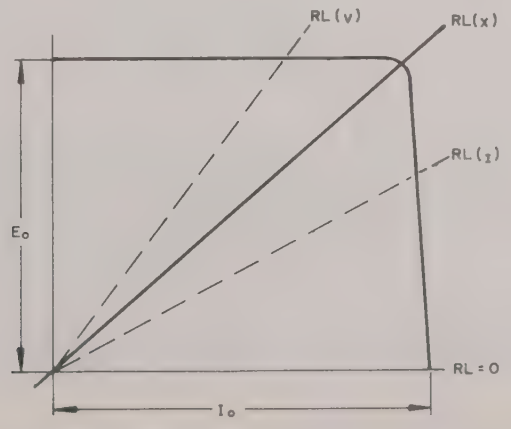


FIG. 4-7 D-C OUTPUT CHARACTERISTICS, OPS GROUPS VI, VII, VIII.

4-32 CIRCUIT DESCRIPTION (See Main Schematic, Section VI, FIG. 6-3)

4-33 For the purpose of analysis, the circuitry of the OPS Power Supply may be divided into several sections which are individually described below. The main schematic (FIG. 6-3) should be used to illustrate the text of this section.

a) A-C INPUT CIRCUIT. A-C line power is introduced through a heavy duty 3-wire line cord (removable)[1] with safety plug. The use of a grounded a-c power outlet will automatically ground the power supply, since the third wire of the line cord is directly connected to the metal chassis and case. Once the A-C POWER SWITCH/CIRCUIT BREAKER (CB101) is closed, the primary of the main transformer (T201), the fan (B201)[2] and a-c pilot light (DS101) will be energized. The two primary windings of the main transformer are either connected in parallel (for 115V a-c nominal line voltage) or in series (for 230V a-c nominal line voltage). The A-C POWER SWITCH/CIRCUIT BREAKER (CB101), aside from switching the a-c primary power, has the function of disconnecting the power supply from the a-c line in case of overloads or short circuits. CB101 has two sensing coils, one of which is always in series with one of the primary windings on T201, whether the main transformer is wired for 115V or for 230V a-c. The second sensing coil of CB101 is in series with secondary winding on T201 which feeds the auxiliary transformer (T202). If an overload occurs, due to either internal component failure or external influences, the coil is energized sufficiently to activate the trip-mechanism of CB101, thus disconnecting the power supply from the a-c line. Since the primary coil of the AUXILIARY POWER TRANSFORMER (T202) is in parallel with the secondary winding on the main transformer (T201) any failure in the auxiliary circuits, reflecting back to the primary of the auxiliary power transformer (T202) will also activate the sensing coil of CB101 and shut down the power supply. A thermal sensing element (S301) is mounted to the HEAT SINK ASSEMBLY (A3)[3] to protect the series regulator transistors from over-temperature. If the preset temperature on S301 is exceeded, its contact close and energize the sensing coil of CB101, resulting once more in the tripping of the A-C POWER SWITCH/CIRCUIT BREAKER and subsequent removal of the a-c input power from the power supply.

b) MAIN D-C SUPPLY. The main d-c power is derived from a center-tapped secondary winding on T201. A full-wave rectifier circuit with silicon diodes (CR301, 302 if located on A3, CR201, 202 if located on main chassis A2) operates into a capacitor input filter (C201, 202 on some models; C201, 202, 203 on others) which is paralleled by a bleeder resistor (R202). The main d-c supply delivers the output current via the series regulator or pass-elements.

c) PASS-ELEMENT SECTION. The pass-element section (Power Output Stage) in the OPS Power Supply varies in complexity according to the output voltage and current rating of the particular model. The NPN silicon pass-transistors of the OPS are located on high-efficiency heat sinks and are cooled by a fan (B201).[2] Some OPS models have single heat sink assemblies (A3) with pass-transistors Q301, to Q3 . ., the number depending on the individual model. Other OPS models have dual heat sink assemblies (A3 and A6) with pass-transistors Q301 to Q3 . ., and Q601 to Q6 . ., the number of transistors again depending on the individual model. While in the low voltage/high output current models ($E_O \leqslant 36$ volts) all pass-transistors are arranged in a parallel circuit, higher voltage models ($E_O > 36$ volts) use a series/parallel configuration in the arrangement of their pass-transistors. In the latter, a "master/slave" circuit is used, where the "slave" section is sometimes paralleled by power resistors, which share in the power dissipation if the power supply is operating in the current-limit mode or under short-circuit conditions. However complex the pass-element section, for analytical purposes, it can be reduced to a single pass-transistor. Electrically, this pass-transistor is part of a series circuit consisting of the unregulated main d-c power supply, the external load and the pass-transistor. The output voltage of the power supply is controlled by changing the series resistance of the control element (the pass-transistor) in the described series circuit. The necessary base-drive for the pass-transistors to affect the change in series resistance is supplied by the "Darlington" connected driver stages. The main driver stages, in turn, receive their base signals from the predriver stage (Q2).

d) VOLTAGE-MODE AMPLIFIER (A_V).

1) The voltage channel of the OPS uses a d-c coupled, high-gain operational amplifier, which functions either as a comparator or a voltage amplifier. With its inverting input connected to the internal d-c reference potential (E_r = CR3 via R4, R8) and resistive feedback (voltage control, R102) to the (−) sensing terminal (TB501−4), a portion of the output voltage is constantly compared to the reference voltage. At equilibrium, the input to the amplifier (A_V) is zero. Any deviation in the output voltage caused by either a source/load variation or by a change in feedback via R102, will tend to produce a difference voltage or "error signal" at the amplifier input. This "error signal" will, after amplification, act as a drive for the pass elements, changing the voltage drop across them in such a way as to bring the output voltage back to the previous value and thus restore equilibrium.

[1] OPS GROUP VIII Models have a non-removable line cord.

[2] OPS GROUP VIII Models have an additional fan (B202), electrically in parallel with B201.

[3] OPS GROUP VIII Models have an addiitonal heat sink assembly (A6) with its own thermal sensing element (S601), electrically in parallel with S301.

2) If the d-c reference is disconnected, the amplifier input can be programmed with external voltage signals. A positive input signal will produce a negative output voltage with reference to the "common" terminal (+ sense). The internal voltage control may serve as a gain control, or an external feedback may be connected.

3) Two lag networks (C9, R16 and C10, R36) are used to stabilize the OPS voltage channel. A ZERO control (R14) with the necessary voltage divider network (R30, R31, R29, CR17, R34) is used to "null" the offset voltage of A_V. Local lead and feedback networks are used to further enhance the dynamic characteristics of the voltage channel (C8, R17, C13, C17, not in all OPS models).

e) CURRENT LIMIT CIRCUIT. The differential input of the current-limit amplifier (Q4, Q5), is connected to the current-sensing resistor (R_S = R203)[1] and to a reference voltage, adjustable by the current limit control (R101). The voltage drop across the current-sensing resistor is thus continuously compared to the reference voltage, set by the current limit control. As long as the voltage developed across R_S (due to load current flow) is less than the preset voltage reference level, the current-limit amplifier will be biased to its inactive state and will not effect the output. If the output current increases, however, the voltage drop across R_S will overcome the reference level set by the current-limit control. The current-limit amplifier will be thus activated and produce a drive signal at the diode gate, greater than A_V, thereby taking control away from the VOLTAGE MODE AMPLIFIER (A_V) and transferring the power supply into the current-limit mode. Since the current-limit amplifier and the voltage amplifier (A_V) are coupled through the diode gate circuit (CR14, CR15) to the predriver stage (Q2), to the amplifier with the greater (negative) output will control the pass transistors and therefore the output. In all OPS models the current channel is programmable via an additional amplifier (A_I) and additional rear terminals (TB206–10, 11, 12). The amplifier (A_I) is coupled via a separate diode to the common diode gate (CR21). It will take control of the pass-elements if its output becomes greater than either the output of the current-limit amplifier (Q4, Q5) or that of the voltage-mode amplifier (A_V).

f) PREDRIVER CIRCUIT. The predriver stage (Q2), working into a fixed, impedance provided by the constant current stage (Q1), amplifies any control signal, orginating from one of the current limit amplifiers or from the voltage mode amplifier, which passes one of the gate diodes (CR14, CR15, CR21).

g) AUXILIARY SUPPLIES

1) AMPLIFIER POWER SUPPLY. This full-wave, bridge rectified source is derived from a secondary winding on the auxiliary transformer (T202). Rectified by CR8, the supply is capacitor-filtered by C2. A current regulator stage (Q3), followed by a string of zener diodes (CR10–13), provides the operating voltage for the voltage-mode amplifier (A_V), the current-control amplifier (A_I).

2) PREDRIVER COLLECTOR SUPPLY. A half-wave rectified (CR3) and capacitor-filtered (C2) supply is derived from a secondary winding on T202. It delivers collector voltage to the predriver stage (Q2).

3) I_{CBO} SUPPLY. This full-wave rectified auxiliary supply is derived from the winding of the auxiliary power transformer. Rectified by CR1 and filtered by C1, constant current is applied to the base of the pass transistors [via the constant current generator stage (Q1)], thus insuring the necessary turn-off bias for these stages under all operating conditions, especially at elevated temperatures.

h) METERING CIRCUIT. Both output voltage and output current are monitored by dual range front panel meters (M101, M102). The two meter ranges are 0 to 10% and 0 to 100% of the rated output voltage and output current and may be selected by meter range switches (S101 for voltage, S102 for current) located between the front panel meters. While the output voltage is measured directly across the error-sensing terminals (TB501–2, TB501–4), the output current is measured indirectly as a voltage drop across the current-sensing resistor (R203).[1]

[1]Model OPS 6–90M has an additional amplifier (A_M, see Main Schematic), which amplifies the sensing voltage drop across R203 by a factor of 20.

SECTION V – MAINTENANCE

5-1 GENERAL

5-2 This section covers maintenance procedures, installation of optional components, calibration and test measurements of the Kepco Model OPS GROUP VIII Power Supplies. Conservative rating of all critical components should keep maintenance problems to a minimum. If trouble does develop, however, the easily removed wrap-around cover and the plug-in feature of the circuit boards provide exceptional accessibility to all components of the supply.

5-3 DISASSEMBLY (Refer to FIG. 5-1)

a) COVER REMOVAL. The wrap-around cover may be taken off by loosening and removing its (17) holding screws, (3) on each side, (6) at the rear, and (5) on the front panel.

b) CIRCUIT BOARD REMOVAL. The printed circuit board is mounted with (2) screws, which are removed from the side. After removal of the four printed circuit board connectors, the board may be lifted from its slide-guide.

c) HEAT SINK REMOVAL. The heat sink assemblies are mounted with (4) screws to the chassis bottom. After the screws are taken out, the wires may be removed by means of the "quick-disconnect" terminals and the assembly may be lifted from the chassis.

d) REASSEMBLY. Reassembly of all components takes place in reverse order of the above described procedures.

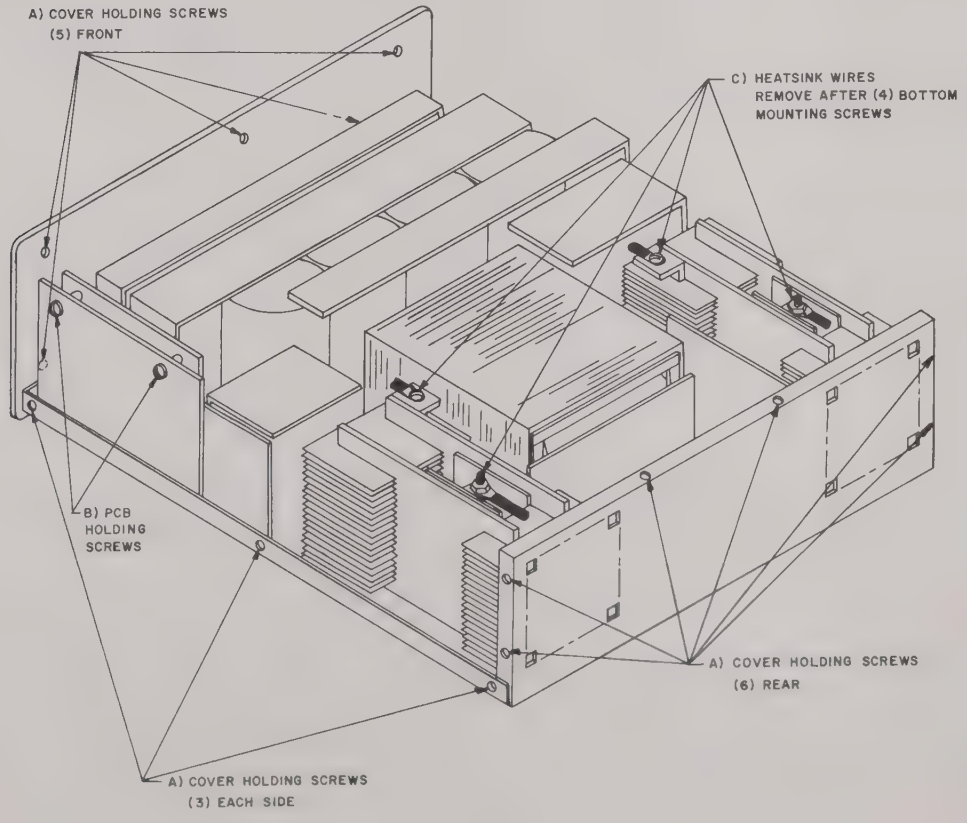


FIG. 5-1 DISASSEMBLY, OPS GROUP VIII.

5-4 INTERNAL ADJUSTMENT PROCEDURES

5-5 GENERAL. Most adjustment procedures have been previously described in Section III of this manual. Refer to Section II, par. 2-3, for a listing of ***all*** procedures.

5-6 MAXIMUM OUTPUT CURRENT ("I_O max adj.") ADJUSTMENT. This adjustment serves as a calibration for the range of the front panel Current Limit Control. The "I_O max adj." (R19) is located on the printed circuit board. (Refer to FIG. 2-1). It is factory-set so that the front panel control covers an output current range of 2—105% of the maximum rated output current. Readjustment of the "I_O max adj." control is needed only if a component in the current limit circuitry must be replaced or, if the range of the front panel control is to be restricted. A convenient way to make the adjustment is as follows:

a) Load the output of the OPS to draw the maximum desired output current with the front panel Current Limit Control fully clockwise. Monitor the output voltage with an oscilloscope, having a vertical sensitivity of at least 0.1 mV/cm.

b) Observe the oscilloscope. Current Limiting is indicated by a sharp increase in output ripple. Locate the "I_O max adj." control and turn slowly until limiting occurs at the point required. Clockwise adjustment will increase the maximum output current range, while counterclockwise adjustment will decrease the range. DO NOT ADJUST TO MORE THAN 105% I_O max. Although this might be possible due to component tolerances, malfunction of the power supply will be caused by exceeding the rated maximum output current.

5-7 LAG NETWORK ADJUSTMENTS. Two a-c stability controls in the form of lag networks have been provided in this power supply (R16—C9 and R36—C10, see main schematic, FIG. 6-3). These networks have been factory-adjusted for maximum amplifier stability when operating into a resistive load. Readjustment is indicated if components, affecting the a-c characteristics of the amplifier must be replaced, or if the load connected to the power supply contains excessive capacity or inductance, causing a-c instability. A-C instability is usually indicated by high frequency oscillation as observed with an oscilloscope across the power supply load. In such cases, the lag networks should be adjusted so that stable operation is restored. If, in extreme cases, adjustment of the lag network should not prove sufficient, twisted load and error-sensing wires or additional capacity directly across the feedback terminals (TB501—6—4) may provide a solution to the problem. See also Section III, par. 3-17.

5-8 TROUBLE SHOOTING

5-9 Modern, high performance power supplies have reached a state of sophistication that requires thorough understanding of the problems involved in repairing complex, solid-state circuitry. Servicing beyond simple part replacement should consequently be attempted only by personnel thoroughly familiar with solid-state component techniques and with experience in closed-loop circuitry.

5-10 Trouble shooting charts, showing resistance and voltage readings, are of very limited usefulness with feedback amplifiers and are not included here. Instead, a detailed circuit description (Section IV), parts location diagrams, simplified functional schematics and a main schematic with all significant voltage readings is presented.

5-11 The following basic steps in case of power supply malfunctioning may also be found useful:

a) If power supply does not function at all: Check all powerline connections and fuses and make certain, power supply is connected to the correct line voltage (it is normally delivered for 115V a-c operation).

b) NO D-C OUTPUT:

1) Check rear barrier-strip jumper connection for correct placement and tight seat. (Refer to FIG. 4-1.)

2) Check the correct placement and tight seat of all transistors and integrated circuit components on the amplifier board. (Refer to the component location drawings and parts list in Section VI.)

3) Check reference voltage from terminal (2) to (8) on the rear barrier-strip. Correct reference potential is 6.2V nominal.

4) Check amplifier supply voltages from "0V d-c" buss. (Refer to Main Schematic, FIG. 6-3.)

5) Test amplifier transistors[1] Q2, Q3, Q4, as well as the I.C. amplifiers.

6) Check the correct mating of all internal printed circuit board connectors.

[1] If a transistor test device is not available, transistors may be checked by means of an ohmmeter. Check between emitter and collector terminals and reverse ohmmeter polarity. One reading should be high, the other low, the ratio between the readings being approximately 1:4.

c) HIGH D-C OUTPUT: If the output voltage is high and not controllable by the voltage control, identical steps as outlined above (par. 5-11b) are advisable. In addition, if the condition persists, check the following:

1) Test the main driver and the power transistors in the pass-element sections by removing the command signal supplied by the control amplifier. This can be accomplished by removing the predriver transistor (Q2). If the output goes to zero, check predriver transistor and concentrate on the main amplifier board (A1). Check I.C.'s and look for burned components. Replace if necessary.

   If the output remains high when the predriver transistor Q2 is removed, the problem exists within the pass-element section. The main driver[1] can be checked by removing it from the heat sink assembly. If this transistor is defective, the output will now go to zero. If the output remains high, a defective pass transistor can be suspected. Confirm by testing the power transistors with an ohmmeter from emmitter to collector. Polarity reversal on the meter leads should produce an approximate 1:4 resistance ratio on "good" transistors. Replace only with listed types, if defective. (See Parts List in Section VI of this manual.)

2) Check the voltage-control resistor (R102) for continuity. Monitor output with an oscilloscope and observe ripple waveform and amplitude. If high frequency oscillations are observed, proceed as directed in par. 5-7. High 60 Hz ripple is often due to failure in one of the rectifier circuits. Measure the operating voltages under the conditions specified in the main schematic (FIG. 6-3).

d) If supply does not function in one of the remote programming modes, disconnect all external components and reconnect internal reference and the voltage control. The following paragraphs refer to the instrument as a power supply, rather than an amplifier in order to simplify test setups and measurements.

e) POOR PERFORMANCE. If the power supply is basically functioning, but poor performance is evident, inspect the test setup to make certain the source of the trouble is not external.

f) Excessive output effects in any of the operating modes are usually traceable to incorrectly connected loads or faulty measurement techniques. Perform measurements as described in par. 5-17 and follow the connecting diagrams.

g) Oscillation of the output voltage or output current is often due to a load with a large inductive component. Twisted load wires of sufficient diameter and held as short as practical, are often the solution to the problem, if lag network adjustment does not correct the trouble. (Refer to par. 5-7.)

5-12 KEPCO Field Engineering Offices or the KEPCO Repair Department will be available for consultation or direct help in difficult service or application problems.

5-13 TEST MEASUREMENTS

5-14 GENERAL. Test measurements to verify the specifications of the operational power supply are often required as a part of incoming inspection following repairs or as a part of a regular maintenance procedure. Adequate test facilities and equipment as well as great care in the performance of these measurements are of prime importance to insure valid results. Since many measurements on operational power supplies and amplifiers require specialized test equipment and rigidly controlled environment conditions, only the more readily verifiable ones are described here.

5-15 MEASUREMENT TECHNIQUES. The importance of proper interconnection of test instruments and the device under test cannot be overemphasized. Indiscriminate connection of measuring devices to the output may cause erroneous readings of d-c output effects, offset parameters or output impedance. The following recommendations should therefore be followed when measurements are to be performed:

a) Connect equipment exactly as shown on the measurement setup diagrams (FIGS. 5-2, 5-3). Do not attempt to measure performance characteristics at the front terminals while drawing load current from the rear terminals (or vice versa).

b) Output current measurements require the use of a high-quality, wirewound measuring resistor which should be of the 4-terminal type and have a low temperature coefficient as well as a wattage rating of at least ten times the actual power dissipated (TEPRO Type TMK or equivalent).

c) Ripple and noise measurements require the strict adherence to sensible equipment grounding practices. There can be only one ground point in a test setup. All equipment is therefore operated off line ground, the equipment cases or ground connections brought to the unit under test, and the latter is then grounded at a single point.

[1] The main driver reference designation differs from model to model. This power transistor is always located on heat sink assembly A3. Its base is connected (via an isolation diode) to the predriver (Q2) collector. See Main Schematic, FIG. 6-3.

5-16 REQUIRED INSTRUMENTATION

a) STABILIZED A-C INPUT SOURCE, with provisions for "stepping" the voltage over the specified a-c input range (105 to 125V *or* 210 to 250V). A variable AUTOTRANSFORMER is generally adequate if it can deliver the required a-c input current.

b) RESISTOR LOAD, variable, capable of dissipating the full d-c output power of the unit under test and equipped with "on-off" and "shorting" switch.

c) D-C VOLTAGE MONITOR, digital or differential voltmeter, able to resolve at least 1 microvolt.

d) OSCILLOSCOPE, vertical sensitivity at least 10 mV/cm and with a minimum bandwidth of 10 megahertz.

e) SQUARE-WAVE GENERATOR, with a variable output amplitude of 0—10 volts into 600 ohms and rise time of at least 0.1 microseconds. A "floating output," where the signal is available either in the positive *or* in the negative direction is desirable.

5-17 D-C MEASUREMENTS. Variations of the offset voltage (ΔE_{io}) and offset current (ΔI_{io}) with a-c input source changes over the specified range, are an excellent indication of the d-c performance of the operational power supply. These measurements may be readily duplicated by following the instructions and diagrams below:

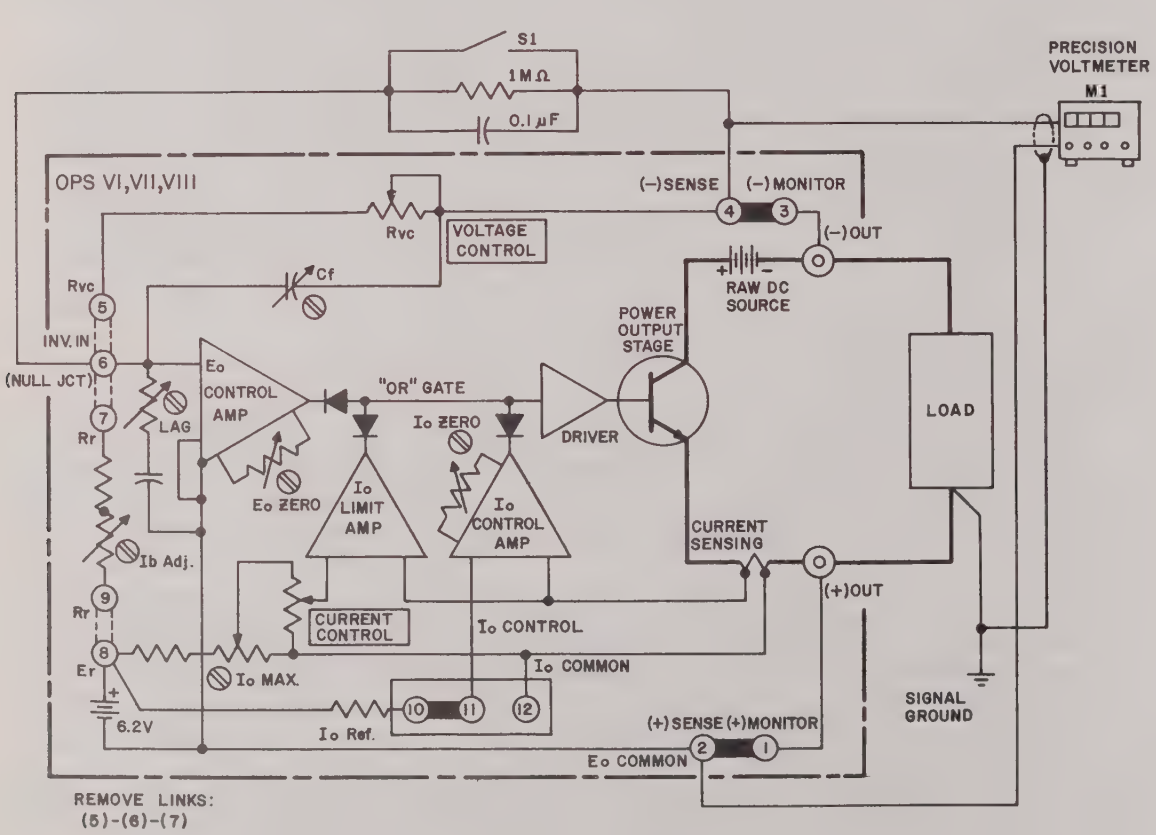


FIG. 5-2 D-C TEST MEASUREMENTS (ΔE_{io}, ΔI_{io}) VS. A-C INPUT SOURCE VARIATIONS.

5-18 PROCEDURE (Refer to FIG. 5-2)

1) To measure ΔE_{io} versus a-c source, ***close*** S1 and read E_{io} (offset voltage) on the digital voltmeter at the output. Vary the a-c input source over the specified range (105–125V ***or*** 210–250V) and note the ***variation*** from the initial reading (ΔE_{io}).

2) To measure ΔI_{io} versus a-c source, ***open*** S1 and read E_o (output voltage). Since the offset current (I_{io}) flows through the feedback resistor (R_f = 1 M ohm) it generates a measurable voltage (E_o) at the output (1 nanoampere of I_{io} generates an output voltage of 1 millivolt for example). Vary the a-c input source over the specified range (105–125V ***or*** 210–250V) and note the ***variation*** from the initial reading (ΔI_{io}).

NOTE: The above described measurements provide an excellent and simple means of checking the d-c performance of the high speed power supply. Measuring offset variations (ΔE_{io}, ΔI_{io}) while changing the load, temperature or over a long time period requires specialized test equipment and a controlled evironment, not readily available in the laboratory. Information concerning these tests may, however, be obtained at the factory.

5-19 DYNAMIC MEASUREMENTS. THE PROGRAMMING TIME CONSTANT and the MAXIMUM SLEWING RATE can be measured using the circuit shown in FIG. 5-3.

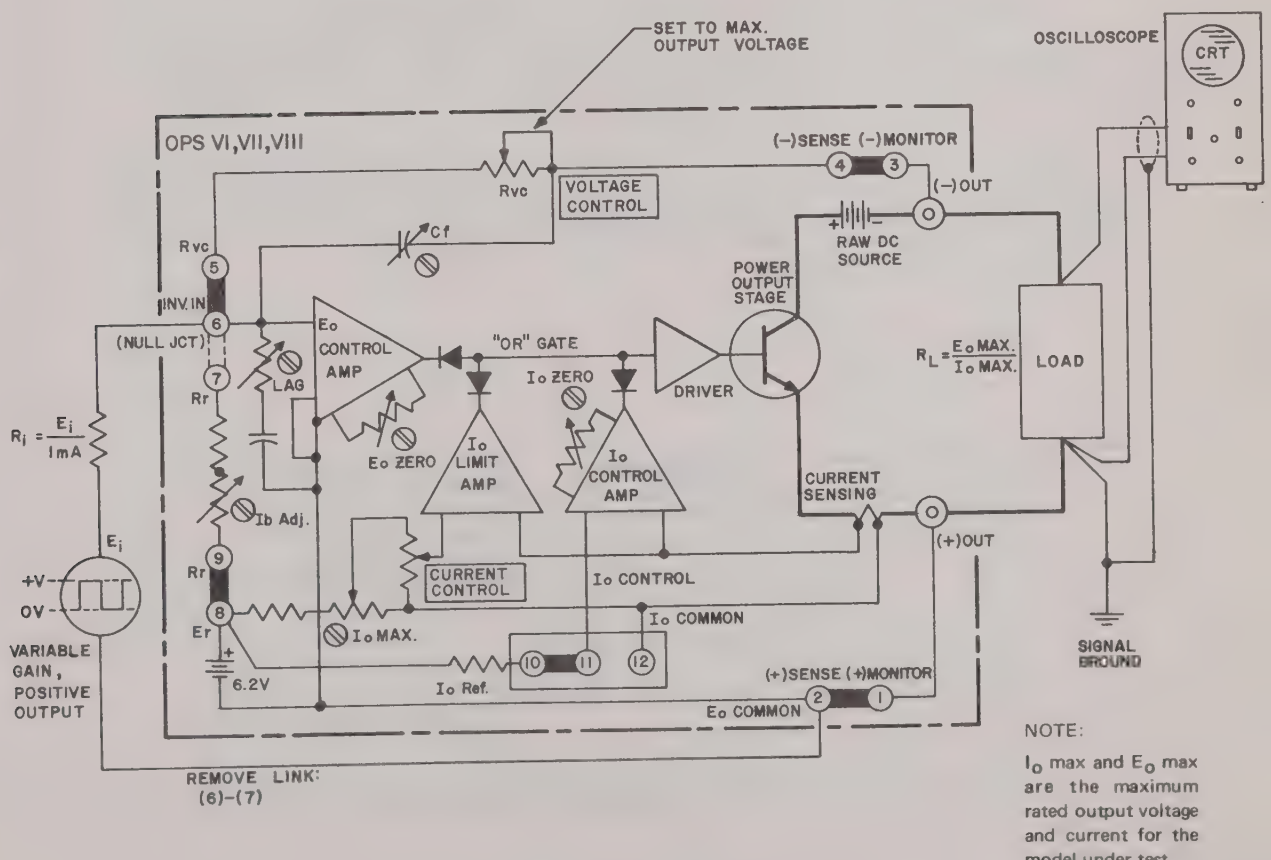


FIG. 5-3 DYNAMIC MEASUREMENTS, VOLTAGE CONTROL CHANNEL.

5-20 PROCEDURE (Refer to FIG. 5-3)

1) To measure the PROGRAMMING TIME CONSTANT, adjust the gain of the square-wave generator (E_i) until the output waveform (displayed on the oscilloscope) shows a peak amplitude equal to the maximum rated output voltage of the OPS model under test. (Refer to FIG. 5-4.)

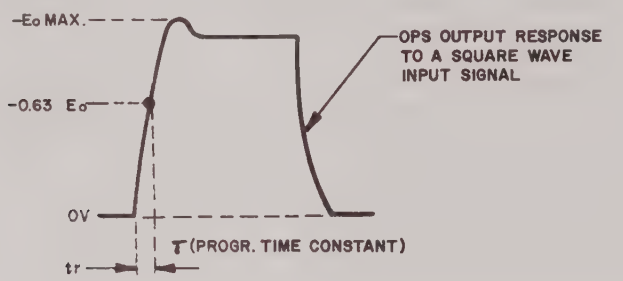


FIG. 5-4 OPS OUTPUT WAVEFORM FOR TIME CONSTANT MEASUREMENTS.

NOTE: Measure the rise time of the displayed waveform from zero (0V) to $-0.63\ E_o$ = ONE TIME CONSTANT). This rise time (t_r) represents the PROGRAMMING TIME CONSTANT

2) To measure the MAXIMUM SLEWING RATE, ***increase*** the gain of the square-wave generator at the input (E_i) until a ***distinct breakpoint*** in the up-slope of the output waveform becomes visible. The slope from "0V" to this breakpoint is the fastest rate of change of which the OPS under test is capable. Make certain that this is true, by slightly increasing the gain of the square-wave generator. The slope (E_o/t_r) should not change. (Refer to FIG. 5-5).

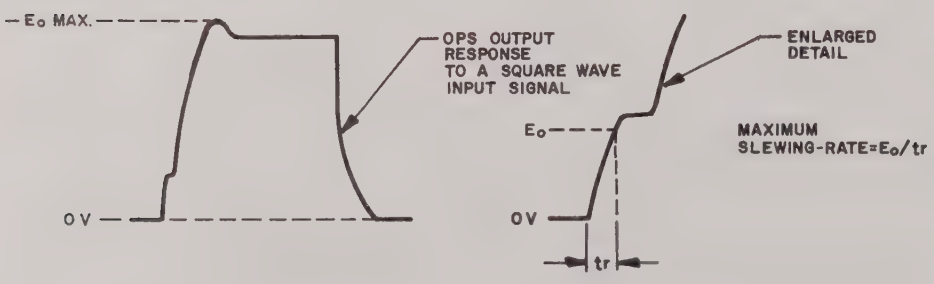


FIG. 5-5 OUTPUT WAVEFORM FOR SLEWING RATE MEASUREMENTS.

NOTE: 1) MEASURE "E_o" (ANY CONVENIENT VALUE ON THE SLOPE).
2) MEASURE "t_r."
3) CALCULATE: MAXIMUM SLEWING RATE = E_o/t_r.

SECTION VI – ELECTRICAL PARTS LIST AND DIAGRAMS

6-1 GENERAL

6-2 This section contains the main schematic, the parts location diagrams, and a list of all replaceable electrical parts. All components are listed in alpha-numerical order of their reference designations. Consult your Kepco Representative for replacement of parts not listed here.

6-3 ORDERING INFORMATION

6-4 To order a replacement part or to inquire about parts not listed in the parts list, address order or inquiry either to your authorized Kepco Sales Representative or to:

KEPCO, INC.
131–38 Sanford Avenue
Flushing, N.Y. 11352

6-5 Specify the following information for each part:

a) Model and complete serial number of instrument.

b) Kepco part number.

c) Circuit reference designator.

d) Description.

6-6 To order a part not listed in the parts list, give a complete description and include its function and location.

NOTE: KEPCO DOES NOT STOCK OR SELL COMPLETE POWER SUPPLY SUBASSEMBLIES AS DESCRIBED HERE AND ELSEWHERE IN THIS INSTRUCTION MANUAL. SOME OF THE REASONS ARE LISTED BELOW:

1) Replacement of a complete subassembly is a comparatively rare necessity.

2) Kepco's subassemblies are readily serviceable, since most of them are of the "plug-in" type.

3) All active components are socket mounted, making replacement extremely easy.

4) The nature of a closed-loop power supply system requires that subassembly replacement is followed by careful measurement of the total power supply performance. In addition, depending on the function of the subassembly, extensive alignment may be required to restore power supply performance to specified values.

IF REPAIRS INVOLVING SUBASSEMBLY REPLACEMENTS ARE REQUIRED, PLEASE CONSULT YOUR LOCAL KEPCO REPRESENTATIVE OR THE KEPCO SALES ENGINEERING DEPARTMENT IN FLUSHING, NEW YORK, N.Y.

KEPCO. REPLACEMENT PARTS LIST

CONTROL CIRCUIT ASSEMBLY (A1), MODEL OPS 150–7M **Code 10-2473**

REFERENCE DESIGNATION	QTY.	DESCRIPTION	MFRS. NAME & PART NO. SEE BOTTOM NOTE	KEPCO PART NO.	REC. SPARE PART QTY.
A_I	1	Int. Circuit Amplifier	Texas Instruments SN72741	250-0025	1
A_V	1	Int. Circuit Amplifier	Kepco, Inc. 250-0013	250-0013	1
C1	1	Capacitor,Elect.,Axial Leads 290 μF, 20V, +100 – 10%	Sangamo Type 052	117-0716	1
C2	1	Capacitor,Elect.,Axial Leads 75 μF, 50V, +75 – 10%	Sangamo Type 556	117-0646	1
C3,4	2	Capacitor,Elect.,Axial Leads 150 μF, 3V, +75 – 10%	Sangamo Type 556	117-0512	1
C7	1	Capacitor,Elect.,Axial Leads 150 μF, 25V, +75 – 10%	Sprague Type 30D	117-0713	1
C8,11,15	3	Capacitor,Mylar,Axial Leads 0.01 μF, 200V, 20%	Sprague Type 192P	117-0353	1
C9	1	Capacitor,Mylar,Axial Leads 0.05 μF, 200V, 20%	Sprague Type 192P	117-0315	1
C10	1	Capacitor,Mylar,Axial Leads 2 μF, 200V, 10%	Industrial Cond. 2LMV200	117-0129	1
C13	1	Capacitor,Mylar,Axial Leads 0.033 μF, 200V, 10%	Sprague Type 192P	117-0291	1
C17	1	Capacitor,Ceramic,Disc. 0.005 μF, 500V, 20%	Radio Materials Type SM	117-0061	1
CR1,6,8	3	Si.,Rectifier,Bridge,Axial Leads 1A, 200V, PIV	General Instrument Type W-02	124-0346	1
CR2,9,10,12, 13,19,20,22	8	Zener Diode,Axial Leads 6.5V, 5%, 250 mW	TRW 121-0028	121-0028	3
CR3,11,17	3	Zener Diode,Axial Leads 5.9–6.2V, 400 mW	Motorola 121-0041	121-0041	1
CR4,5	2	Si.,Rectifier Diode 100V, PIV – 5 μA @ 0.5V	Semicon 124-0178	124-0178	1
CR7,14, 15,21	4	Si.,Rectifier Diode 1.5A, 100V, PIV	Semicon Type SI-1	124-0133	2
CR16,18	2	Si.,Rectifier Diode 1A, 400V, PIV	Semicon Type SI-4	124-0028	1
Q1	1	Transistor,Silicon,NPN Small Signal	RCA 2N3584	119-0104	1
Q2	1	Transistor,Silicon,NPN Small Signal	Semiconductor 119-0094	119-0094	1
Q3	1	Transistor,Silicon,NPN Small Signal	RCA 2N3053	119-0059	1
Q4,5	2	Transistor,Silicon,NPN Small Signal	Texas Instruments 2N5450	119-0093	1

NOTE: REPLACEMENT PARTS MAY BE ORDERED FROM KEPCO, INC. ORDERS SHOULD INCLUDE KEPCO PART NUMBER AND DESCRIPTION.

PLEASE NOTE: THE MANUFACTURER'S NAME AND PART NUMBER LISTED FOR EACH ITEM ON REPLACEMENT PARTS LISTS REPRESENTS AT LEAST ONE SOURCE FOR THAT ITEM AND IS LISTED SOLELY FOR THE CONVENIENCE OF KEPCO EQUIPMENT OWNERS IN OBTAINING REPLACEMENT PARTS LOCALLY. WE RESERVE THE RIGHT TO USE EQUIVALENT ITEMS FROM ALTERNATE SOURCES. KEPCO, INC.

KEPCO. REPLACEMENT PARTS LIST

CONTROL CIRCUIT ASSEMBLY (A1), MODEL OPS 150–7M **Code 10-2473**

REFERENCE DESIGNATION	QTY.	DESCRIPTION	MFRS. NAME & PART NO. SEE BOTTOM NOTE	KEPCO PART NO.	REC. SPARE PART QTY.
R1	1	Resistor,Fixed,Molded 120 ohm, 1/2 W, 5%	Allen Bradley EB1215	115-0903	1
R2	1	Resistor,Fixed,Metal-Glaze 3 k ohm, 1/4 W, 5%	IRC Type RG-1/4	115-2294	1
R3	1	Resistor,Fixed,M.G. 560 ohm, 1/4 W, 5%	IRC Type RG-1/4	115-2437	1
R4	1	Resistor,Variable,W.W. 1 k ohm, 1/2 W, 10%	Bourns Type 3007P	115-2264	1
R5	1	Resistor,Fixed,Molded 560 ohm, 1/4 W, 10%	IRC Type GBT-1/4	115-2210	1
R6,15	2	Resistor,Fixed,Precision,M.F. 10 k ohm, 1/8 W, 1%	Dale Type MFF-1/8	115-2174	1
R7,29	2	Resistor,Fixed,Precision,M.F. 750 ohm, 1/8 W, 1%	Dale Type MFF-1/8	115-2259	1
R8	1	Resistor,Fixed,Precision,W.W. 5.7 k ohm, 1 W, 1%	Tepro Type TS-1W	115-1301	1
R9,34	2	Resistor,Fixed,Precision,M.F. 210 ohm, 1/8 W, 1%	Dale Type MFF-1/8	115-2177	1
R10	1	Resistor,Fixed,Metal-Glaze 82 k ohm, 1/4 W, 5%	IRC Type RG-1/4	115-2012	1
R11	1	Resistor,Fixed,Molded 3.9 k ohm, 1/2 W, 5%	Allen Bradley EB3905	115-0808	1
R14	1	Resistor,Variable,Cermet 100 k ohm, 3/4 W, 10%	Bourns Type 3009P	115-2399	1
R16	1	Resistor,Variable,Cermet 500 ohm, 3/4 W, 10%	Bourns Type 3009P	115-2398	1
R17	1	Resistor,Fixed,Molded 47 ohm, 1/4 W, 10%	IRC Type GBT-1/4	115-2273	1
R18	1	Resistor,Fixed,Molded 47 k ohm, 1/4 W, 10%	IRC Type GBT-1/4	115-2237	1
R19	1	Resistor,Variable,Cermet 20 k ohm, 3/4 W, 10%	Bourns Type 3009P	115-2393	1
R20	1	Resistor,Fixed,Metal-Glaze 6.2 k ohm, 1/4 W, 5%	IRC Type RG-1/4	115-2258	1
R21	1	Resistor,Fixed,Molded 12 k ohm, 1/4 W, 10%	IRC Type GBT-1/4	115-2276	1
R23	1	Resistor,Fixed,Molded 82 ohm, 1/2 W, 5%	Allen Bradley EB8205	115-1243	1
R26	1	Resistor,Fixed,Molded 1 k ohm, 1/4 W, 10%	IRC Type GBT-1/4	115-2238	1
R27	1	Resistor,Fixed,Molded 10 ohm, 1/4 W, 10%	IRC Type GBT-1/4	115-2230	1
R28	1	Resistor,Fixed,M.G. 1.2 k ohm, 1/4 W, 5%	IRC Type RG-1/4	115-2505	1
R30,31	2	Resistor,Fixed,Precision,M.F. 43.2 k ohm, 1/8 W, 1%	Dale Type MFF-1/8	115-2380	1
R33	1	Resistor,Fixed,Molded 2.2 k ohm, 1/4 W, 10%	IRC Type GBT-1/4	115-2382	1

NOTE: REPLACEMENT PARTS MAY BE ORDERED FROM KEPCO, INC. ORDERS SHOULD INCLUDE KEPCO PART NUMBER AND DESCRIPTION.

PLEASE NOTE: THE MANUFACTURER'S NAME AND PART NUMBER LISTED FOR EACH ITEM ON REPLACEMENT PARTS LISTS REPRESENTS AT LEAST ONE SOURCE FOR THAT ITEM AND IS LISTED SOLELY FOR THE CONVENIENCE OF KEPCO EQUIPMENT OWNERS IN OBTAINING REPLACEMENT PARTS LOCALLY. WE RESERVE THE RIGHT TO USE EQUIVALENT ITEMS FROM ALTERNATE SOURCES. KEPCO, INC.

CONTROL CIRCUIT ASSEMBLY (A1), MODEL OPS 150–7M

Code 10-2473

REFERENCE DESIGNATION	QTY.	DESCRIPTION	MFRS. NAME & PART NO. SEE BOTTOM NOTE	KEPCO PART NO.	REC. SPARE PART QTY.
R35	1	Resistor,Fixed,M.G. 960 ohm, 1/8 W, 1%	Dale Type MFF-1/8	115-2479	1
R36	1	Resistor,Variable,Cermet 10 ohm, 3/4 W, 10%	Bourns Type 3009P	115-2397	1
R38,39	2	Resistor,Fixed,Precision,M.F. 1 k ohm, 1/8 W, 1%	Dale Type MFF-1/8	115-2180	1
R41	1	Resistor,Variable,W.W. 10 k ohm, 3/4 W, 10%	Bourns Type 3009P	115-2481	1
R42	1	Resistor,Fixed,Precision,M.F. 301 ohm, 1/8 W, 1%	Dale Type MFF-1/8	115-2261	1
R44	1	Resistor,Fixed,Precision,M.F. 9.09 k ohm, 1/4 W, 1%	Dale Type MFF-1/4	115-1998	1

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KEPCO. REPLACEMENT PARTS LIST

MAIN CHASSIS AND FRONT PANEL ASSEMBLY (A2), MODEL OPS 150–7M **Code 10-2473**

REFERENCE DESIGNATION	QTY.	DESCRIPTION	MFRS. NAME & PART NO. SEE BOTTOM NOTE	KEPCO PART NO.	REC. SPARE PART QTY.
FRONT PANEL ASSEMBLY CONTAINS:					
CB101	1	Circuit Breaker, 2 Pole 15A/1A	Heinemann JA2Z79-2	127-0287	1
DS101	1	Pilot Light Assembly	Industrial Devices Glo-Dot 2100	152-0087	2
M101	1	Meter 0–8A, d-c	Jewell Instruments Type 81 T	135-0453	0
M102	1	Meter 0–15V, d-c	Jewell Instruments Type 81 T	135-0472	0
R101	1	Resistor,Variable,Composition 2 k ohm, 1/2 W, 30%	C.T.S. Type VA-45	115-2268	1
R102	1	Resistor,Variable,WW 150 k ohm, 3 W, 3%	IRC Type 8400	115-1223	1
S102,103	2	Switch,Slide DPDT – Shorting Type	Stackpole Type SS-72-1	127-0254	0
CHASSIS ASSEMBLY CONTAINS:					
B201,202	2	Motor,Fan	Howard Industries 23112	148-0027	1
C201,202,203, 204,205,206	6	Capacitor,Electrolytic,Can 1.9 k μF, 250V	General Electric Type 86F	117-0683	2
C207,208	2	Capacitor,Ceramic,Axial Leads 0.01 μF, 2 kV	Radio Materials Type Z5U	117-0059	1
C210	1	Capacitor,Variable,Ceramic 390–1400 pF, 350V	Arco Type PC-4615	117-0578	1
C211	1	Capacitor,Mylar,Axial Leads 0.0022 μF, 200V, 10%	Sprague Type 192P	117-0659	1
CR201,202	2	Rectifier,Silicon,Stud 500V PIV, 15A	General Electric 1N3213	124-0213	1
CR204	1	Rectifier,Silicon,Axial Leads 400V PIV, 5A	Semicon S-5A4	124-0348	1
L201	1	Choke,Filter	Kepco Magnetics 100-1876	100-1876	1
R201	1	Resistor,Fixed,Power,Axial 7.5 ohm, 5 W, 5%	Tepro Type TS-5W	115-0982	1
R202	1	Resistor,Fixed,Power,Strip 10 k ohm, 10 W, 5%	Hardwick Hindle 3/4 BRS-56-10K	115-1606	1
R203	1	Resistor,Fixed,Power,Shunt 0.0625 ohm, 50 W, 1%	Tepro TMK-50W	115-1384	1
R204,205	2	Resistor,C.T.,Power Ribbon 63.2 ohm, 700 W, 5%	Kepco Magnetics 115-2503	115-2503	1
R206	1	Resistor,Fixed,Power 5 k, 10 W, 5%	Ward Leonard 10S5000	115-1719	1
T201	1	Transformer,Main	Kepco Magnetics 100-1894	100-1894	1
T202	1	Transformer,Auxiliary	Kepco Magnetics 100-1899	100-1899	1

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KEPCO. REPLACEMENT PARTS LIST

HEAT SINK ASSEMBLY (A3), MODEL OPS 150–7M **Code 10-2473**

REFERENCE DESIGNATION	QTY.	DESCRIPTION	MFRS. NAME & PART NO. SEE BOTTOM NOTE	KEPCO PART NO.	REC. SPARE PART QTY.
C301	1	Capactior,Mylar,Axial Leads 0.05 μF, 200V	Sprague Type 192P	117-0315	1
C303	1	Capacitor,Mylar,Axial Leads 0.01 μF, 200V, 20%	Sprague Type 192P	117-0353	1
CR301	1	Rectifier,Silicon,Axial Leads 400V PIV, 1A	Semicon Type SM-140	124-0028	1
Q301,302,303, 304,305,306, 307,308	8	Transistor,NPN,Power	Solid Power 119-0109	119-0109	3
Q309	1	Transistor,NPN,Power	Westinghouse 119-0071	119-0071	1
R301,302,303, 304,306,307, 308,309	8	Resistor,Fixed,Power,Axial 0.3 ohm, 3 W, 3%	Tepro Type TS-3W	115-2139	2
R305,310	2	Resistor,Fixed,Molded 100 ohm, 1/4 W, 10%	IRC Type GBT-1/4	115-2231	1
R311	1	Resistor,Fixed,Molded 1 k ohm, 1/4 W, 10%	IRC Type GBT-1/4	115-2238	1
S301	1	Thermostat,N.O. 260 °F ±10°F	Stemco 110486	127-0248	0

NOTE: REPLACEMENT PARTS MAY BE ORDERED FROM KEPCO, INC. ORDERS SHOULD INCLUDE KEPCO PART NUMBER AND DESCRIPTION.

PLEASE NOTE: THE MANUFACTURER'S NAME AND PART NUMBER LISTED FOR EACH ITEM ON REPLACEMENT PARTS LISTS REPRESENTS AT LEAST ONE SOURCE FOR THAT ITEM AND IS LISTED SOLELY FOR THE CONVENIENCE OF KEPCO EQUIPMENT OWNERS IN OBTAINING REPLACEMENT PARTS LOCALLY. WE RESERVE THE RIGHT TO USE EQUIVALENT ITEMS FROM ALTERNATE SOURCES. KEPCO, INC.

KEPCO. REPLACEMENT PARTS LIST

HEAT SINK ASSEMBLY (A6), MODEL OPS 150–7M **Code 10-2473**

REFERENCE DESIGNATION	QTY.	DESCRIPTION	MFRS. NAME & PART NO. SEE BOTTOM NOTE	KEPCO PART NO.	REC. SPARE PART QTY.
C601	1	Capacitor,Mylar,Axial Leads 200 pF, 1 kV	Radio Materials Type JF	117-0571	1
C602	1	Capacitor,Mylar,Axial Leads 0.02 μF, 200V, 10%	Sprague Type 192P	117-0377	1
CR601	1	Zener Diode 6.5V, ±5%, 250 mW	Transitron 1N763-1	121-0028	1
Q601,602,603, 604,607,608, 609,610	8	Transistor,Silicon,Power,NPN	Solid Power 119-0109	119-0109	3
Q605,611	2	Transistor,NPN,Silicon,Power	Westinghouse 119-0071	119-0071	1
Q606	1	Transistor,NPN,Silicon,Power	Semiconductor 119-0079	119-0079	1
R601,602,603, 604,609,610, 611,612	8	Resistor,Fixed,Power,Axial 0.3 ohm, 3 W, 3%	Tepro Type TS-3W	115-2139	2
R605,614	2	Resistor,Fixed,Molded 100 ohm, 1/4 W, 10%	IRC Type GBT-1/4	115-2231	1
R606,615	2	Resistor,Fixed,Molded 1 k ohm, 1/4 W, 10%	IRC Type GBT-1/4	115-2238	1
R607,608	2	Resistor,Fixed,Power,Axial 12 k ohm, 3 W, 5%	Tepro Type TS-3W	115-2194	1
R613	1	Resistor,Fixed,Molded 22 ohm, 1/4 W, 10%	IRC Type GBT-1/4	115-2494	1
R616	1	Resistor,Fixed,Power,Axial 5 k ohm, 5 W, 5%	Tepro Type TS-5W	115-0232	1
R617	1	Resistor,Fixed,Molded 150 ohm, 1/2 W, 10%	Allen Bradley EB1511	115-0543	1
S601	1	Switch,Thermostat,N.O. 260 °F ±10°F	Stemco 110486	127-0248	0

MISCELLANEOUS PARTS:

	2	Control Knobs	155-0050	0
	2	Handle	139-0197	0
TB501	1	Terminal Assembly with 9 Terminal Barrier-Strip	236-0555	0
	4	Foot	158-0004	0
	2	Fan Blade	149-0023	0
	1	Cabinet Cover	129-0120	0
TB206	1	3 Terminal Barrier-Strip	167-0736	0

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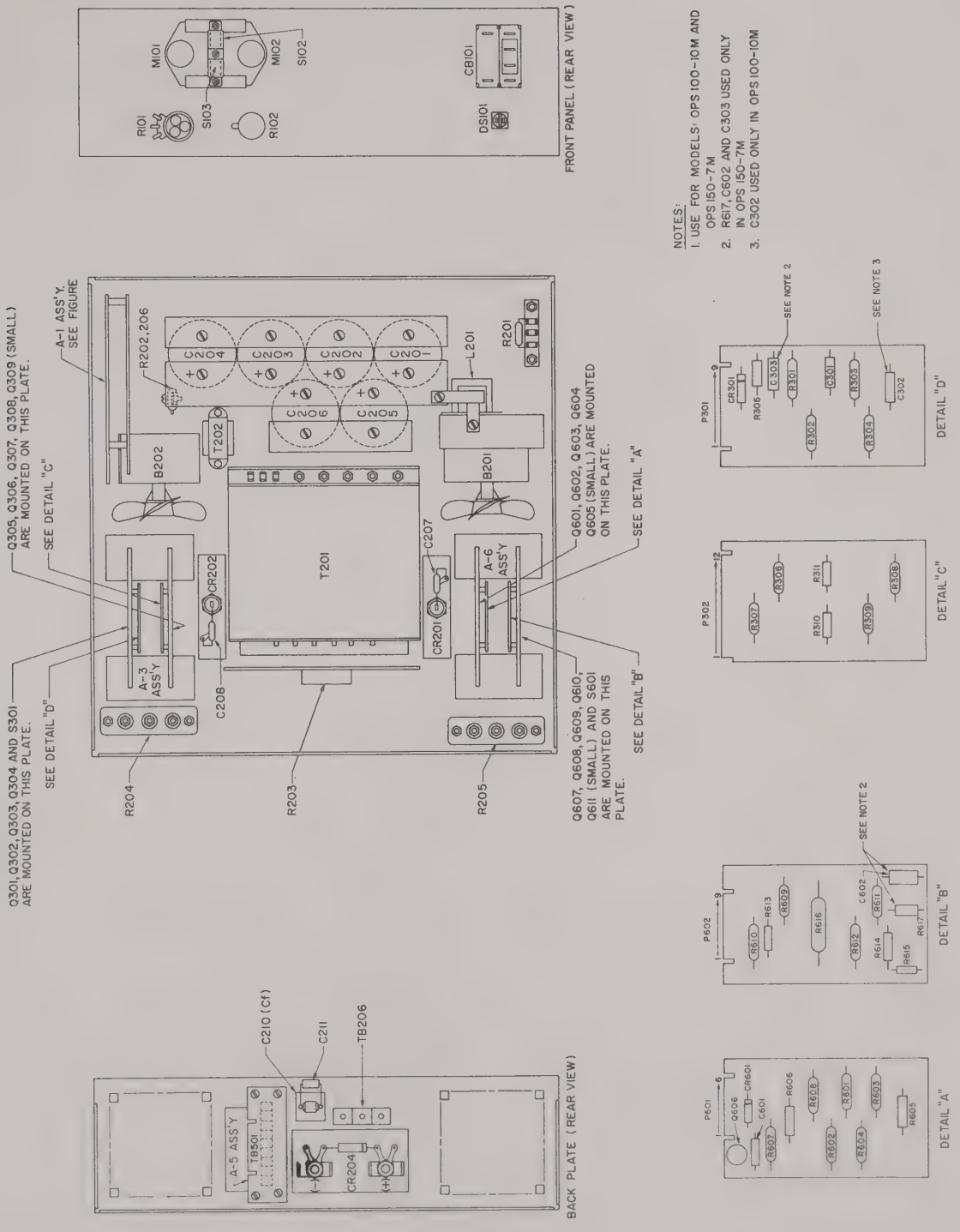
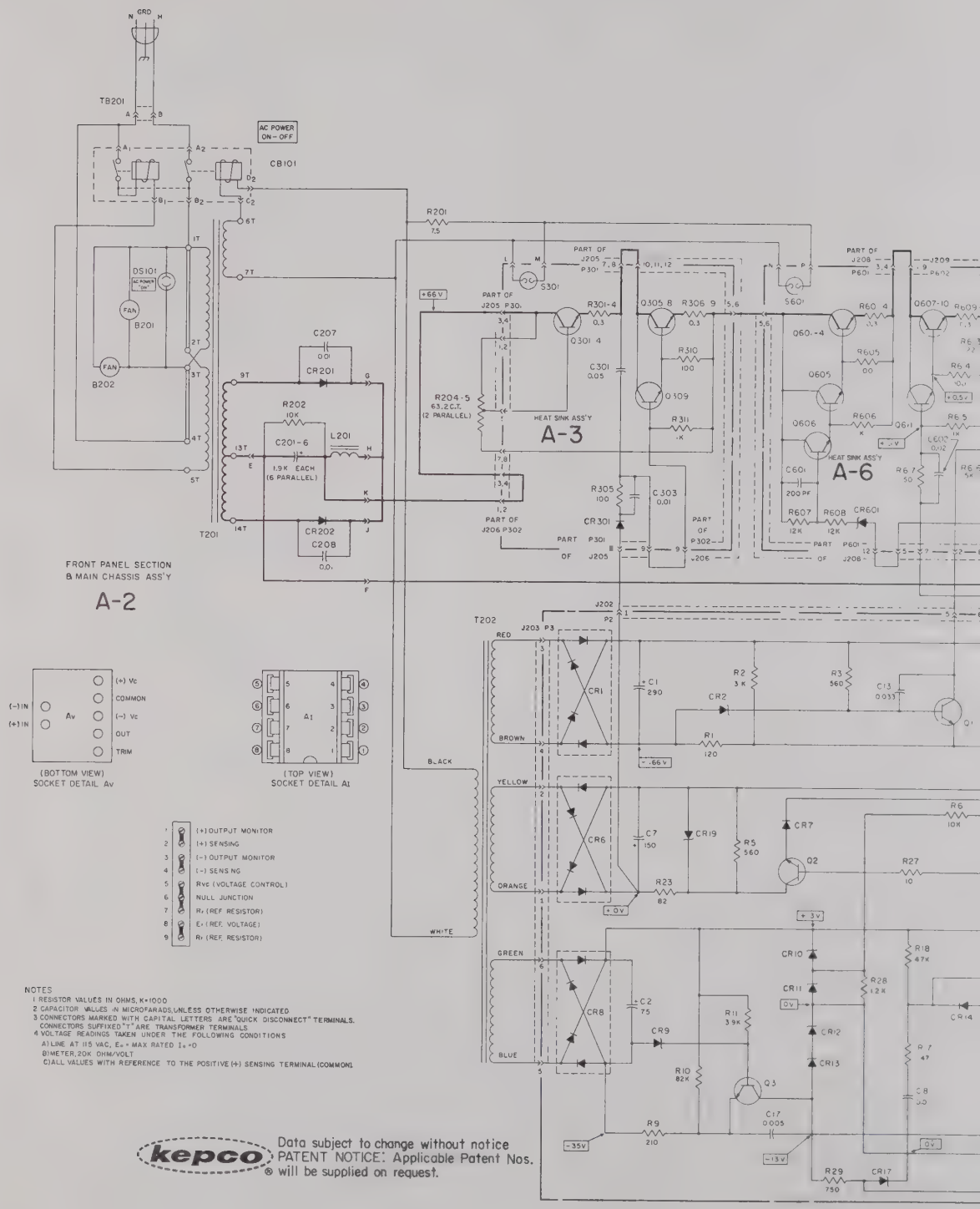


FIG. 6-1 COMPONENT LOCATION, MAIN CHASSIS (A2) AND HEAT SINK ASSEMBLIES (A3).



NOTES
1 RESISTOR VALUES IN OHMS, K=1000
2 CAPACITOR VALUES IN MICROFARADS, UNLESS OTHERWISE INDICATED
3 CONNECTORS MARKED WITH CAPITAL LETTERS ARE "QUICK DISCONNECT" TERMINALS. CONNECTORS SUFFIXED "T" ARE TRANSFORMER TERMINALS
4 VOLTAGE READINGS TAKEN UNDER THE FOLLOWING CONDITIONS
A) LINE AT 115 VAC, E_o = MAX RATED I_o = 0
B) METER, 20K OHM/VOLT
C) ALL VALUES WITH REFERENCE TO THE POSITIVE (+) SENSING TERMINAL (COMMON)

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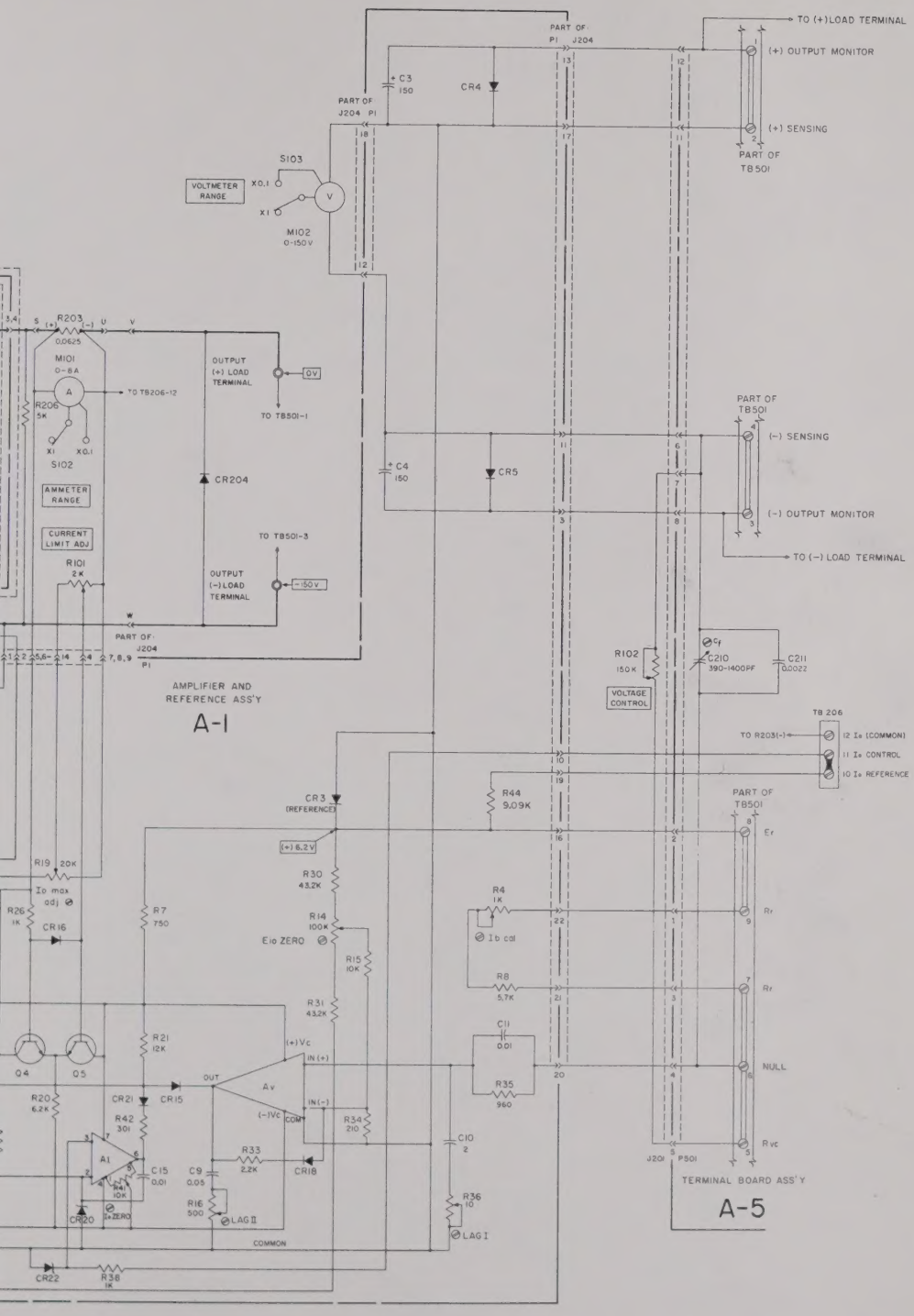
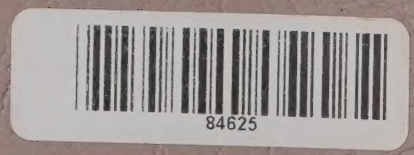


FIG. 6-3 MAIN SCHEMATIC DIAGRAM, MODEL OPS 150–7M.



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